An Insulating Glass Knowledge Base
Phase II Final Report

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Disclaimer

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Abstract

This report will discuss issues relevant to Insulating Glass (IG) durability performance by presenting the observations and developed conclusions in a logical sequential format. This concluding effort discusses Phase II activities and focuses on beginning to quantifying IG durability issues while continuing the approach presented in the Phase I activities (Appendix 1) which discuss a qualitative assessment of durability issues.

Phase II developed a focus around two specific IG design classes previously presented in Phase I of this project. The typical box spacer and thermoplastic spacer design including their Failure Modes and Effect Analysis (FMEA) and Fault Tree diagrams were chosen to address two currently used IG design options with varying components and failure modes. The system failures occur due to failures of components or their interfaces. Efforts to begin quantifying the durability issues focused on the development and delivery of an included computer based IG durability simulation program.

The focus/effort to deliver the foundation for a comprehensive IG durability simulation tool is necessary to address advancements needed to meet current and future building envelope energy performance goals. This need is based upon the current lack of IG field failure data and the lengthy field observation time necessary for this data collection. Ultimately, the simulation program is intended to be used by designers throughout the current and future industry supply chain. Its use is intended to advance IG durability as expectations grow around energy conservation and with the growth of embedded technologies as required to meet energy needs. In addition the tool has the immediate benefit of providing insight for research and improvement prioritization.

Included in the simulation model presentation are elements and / or methods to address IG materials, design, process, quality, induced stress (environmental and other factors), validation, etc. In addition, acquired data is presented in support of project and model assumptions. Finally, current and suggested testing protocol and procedure for future model validation and IG physical testing are discussed.

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List of Acronyms

AAMA - American Architectural Manufacturers Association

ASHRAE – American Society of Heating, Refrigeration and Air-Conditioning

ASTM – American Society for Testing and Materials

GANA - The Glass Association of North America

U.S. DOE / DOE – United States Department of Energy

Dll – dynamically linked library

EOS – Equation of State

FMEA – Failure Modes and Effects Analysis

GANA – Glass Association of North America

GUI – Graphical Users Interface

IG – insulating glass unit (panel, lite)

IGCC – Insulating Glass Certification Council

IGDB – International Glazing Database

IGMA – Insulating Glass Manufacturers Alliance

ISO – International Standards Organization

LBNL – Lawrence Berkley National Laboratory

LRC – Loading Ratio Correlation

MVTR – Moisture Vapor Transmission Rate

NFRC – National Fenestration Rating Council

NOAA – National Oceanic and Atmospheric Administration

PIB – polyisobutylene

RH – relative humidity

SCM – Supply Chain Management

SEVP – Severity Factor – pressure

SEVT- Severity Factor – temperature

SEVV- Severity Factor- vapor pressure

SHGC – Solar Heat Gain Coefficient

SIGMA- Sealed Insulating Glass Manufacturers Association

TMY / TMY2 – Typical Meteorological Year

TPS – Thermal Plastic Spacer

UV – ultra violet

Executive Summary

Michael L .Doll

The Window Industry Technology Roadmap, sponsored by the U.S. Department of Energy's Office of Building, State, and Community Programs, identified durability of windows as being a barrier to the advancement of this product. This subgroup identified three actions to overcome this barrier. These are: (1) establishing a system for rating durability of products, (2) defining appropriate durability and warranty periods for different window components, and (3) developing products that encourage consumer upgrade as features advance.

This report addresses the first two of these issues by developing a public domain knowledge base that can be used by standards organizations to create consensus standards that directly impact IG unit durability. This effort encompassed technology maturation stages 2 and 3. The objectives of the technology maturation stage 2 efforts are two-fold: quantifying durability of existing IG unit subcomponents and understanding and quantifying the mechanisms of subsystem and system failure. The objective of the technology maturation stage 3 efforts are also two-fold: developing a predictive tool to assist designers in developing sufficiently durable IG units and development of accelerated test protocols that correlate to field service lifetime. All of the efforts within this project have been documented in this public domain Insulated Glass Knowledge Base to support standardization of IG unit durability methods and rating measures development.

This report is the culmination of work initiated by a team which included the Department of Energy (DOE) and the Insulating Glass Industry with representation from their customers and their supply chain. Insulating glass products play a pivotal role in meeting the DOE performance goals for current and future building envelopes. Several developing technologies such as Electrochromics, advanced coatings and dynamic thermal control have great potential for meeting required energy goals, however current IG unit durability is questionable. Although data is lacking regarding IG unit durability, there is a growing perception of costly IG unit failure rates that creates a barrier to new technology implementation and associated costs.

From those discussions and concerns, this project was defined and designated as An Insulating Glass Knowledge Database to archive current and future durability information. Additionally, analysis tools and methodologies would be presented in support of a continuous improvement process of designing, manufacturing and application of quality IG units.

Initiation of the project recognized several major challenges which must be addressed for creating and maintaining a successful knowledge base. Among these challenges are industrial participation and knowledge contribution, varying definitions of “durable IG units” along with “failed IG units” and the dissemination, communication and implementation to and in small and large organizations. In consideration of these challenges, the following project tasks were defined and are detailed in the remainder of this report. Each is also included as a solicitation to the industry for continuing support and contribution of field and laboratory data. This supports characterization of current IG unit failure rates and modes of failure through use of material property data, laboratory and field IG unit testing data, design methodology and tools, business and customer IG unit durability expectations, volumes and regions of sales, etc. In addition, each task considers an element of further advancing IG unit design, materials, manufacturing, quality and application.

Tasks

Task 1	Review of current literature
Task 2	Determine current system durability of representative IG products
Task 3	Investigate and quantify failure mechanisms
Task 4	Develop predictive durability design tool
Task 5	Develop protocol for accelerated test correlated to service life
Task 6	Report preparation and submittal

Although it is believed that IG product liability and differentiation continue to discourage sharing knowledge, data contribution, and dissemination of information, several key contributions of research, theoretical analysis, and hypothesis detailed in this report have led to a deeper understanding of the current situation. This emphasizes the need to prioritize and address continuing efforts to insure continued development and application of efficient and durable IG units.

Insulating Glass – Proactive Failure Identification and Product Specification

Large IG manufactures generally support a comprehensive set of specifications for the IG products they produce. The shear volume of product requires a need for efficient, repeatable processes that require an understanding and documented expectation of raw materials, design, process and quality. In addition, these larger organizations are continually improving their designs, materials, etc. achieving cost advantages and product differentiation in the market. The smaller IG assembly organizations generally work from a different business model. They generally purchase an IG system. The supply chain (glass, sealants, desiccants, spacers, etc.) recommends the materials and process for the IG unit fabrication. There is little motivation for the small IG assembler to have an in-house comprehensive understanding of the material requirements, material interfaces, processing requirements, etc. as each follows the supply chain recommendations and focuses more on cost efficiency in raw material purchasing and IG assembly.

The choices of IG unit materials (sealants, spacer systems, etc.) and the combinations of these choices are staggering. Yet, each combination represents a unique IG design and the possibility of a unique set of failures which will define the unit's durability over time.

General research efforts addressing IG unit durability have been and continue to be focused at understanding IG unit seal systems and their materials. Although, as an example, permeation of liquids, vapors, and gases of the sealant materials is an important aspect of IG unit durability, this project was defined and brings focus to identifying and evaluating all modes of root cause IG unit failure. This process requires that each IG product be considered as a unique system of design materials, process assembly, etc. As demonstrated, a Failure Modes and Effects Analysis (FMEA) documents the possible root cause failure modes (not always recognizable through observation or testing) of the system. The FMEA can then support a Fault or Event Tree Diagram, FIG. A, which traces the root cause failure (top level) down to a defined symptomatic, more easily recognizable level of failure such as surface condensation.

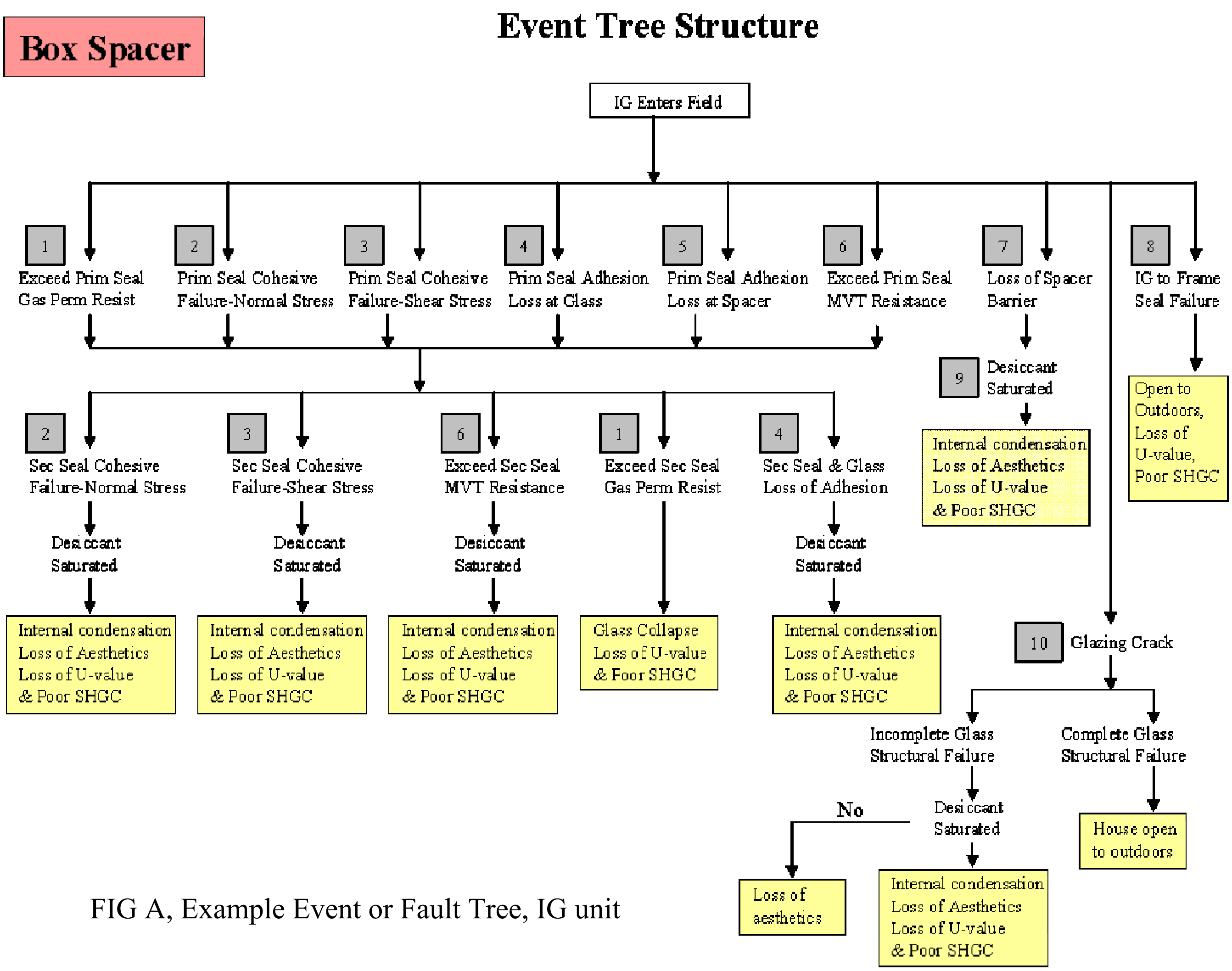


FIG A, Example Event or Fault Tree, IG unit

The level of detail required in the FMEA and a resulting fault tree is dependent on the system being addressed. Figure A is an example and does not contain the level of detail expected to comprehensively define all expected modes of failure which may exist in current IG products.

For instance, the example in Figure A is more closely related to an IG unit design that does not include glass coatings. Failure modes identified with coatings and their processes would be addressed in the FMEA discussion and documented, possibly adding additional nodes or refining the definition of an exiting node.

It is recommended that FMEA, or a similar tool, be used to begin to define and document a specific IG product's design, materials, process requirements, etc. and their relationship (possible failure modes) to durability expectations. For many IG unit manufactures, initially this process will lead to more questions than answers in defining and understanding the current product that they produce. This is a good thing and highlights the need to understand and support the following recommendations.

As referenced above, there is little or no data which explicitly defines current IG unit failure rates. A current Insulating Glass Manufactures Alliance (IGMA) field study and contribution of anonymous laboratory data at the very least suggests that IG units that are designed and produced to withstand more rigorous laboratory testing have shown to be more durable in the field. At the same time, laboratory data shows that IG units that will fail will most likely be infant failures, lasting a year or two. And, many of these failures may not be observed for years after initial material or component failure; when conditions allow for an observable symptomatic response. The process of evaluating the root cause at these data points requires a clear understanding of the units which were being tested and installed in the field. The lack of clear, comprehensive specifications and identification on many of the units makes it difficult or impossible to suggest or correlate root cause failure.

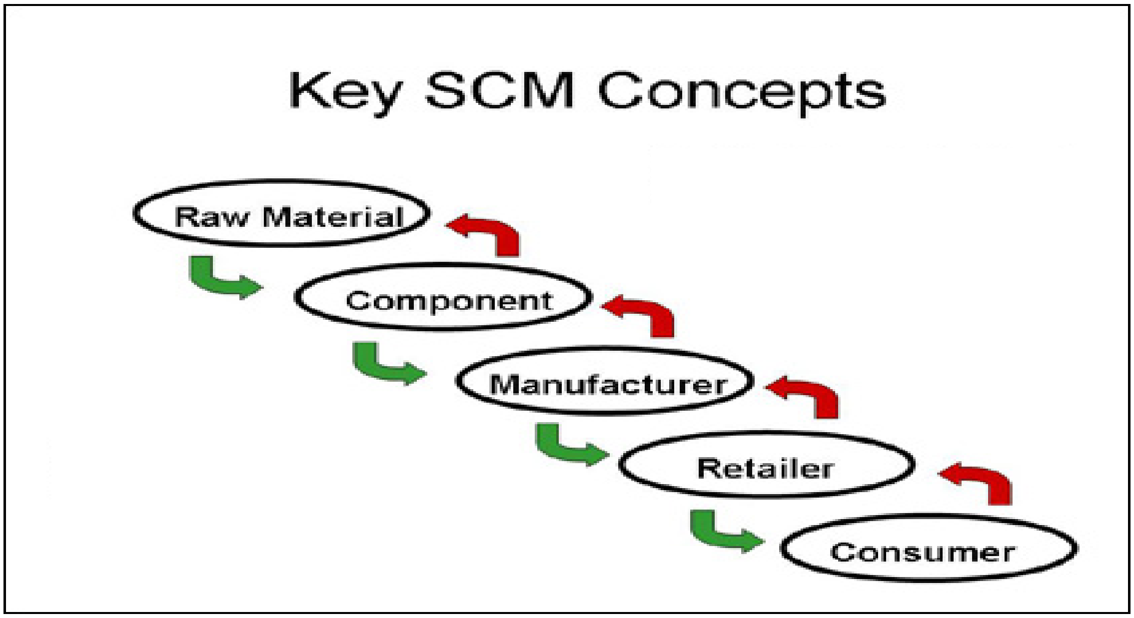
It is recommended that identification, product and process specifications be developed defining IG products produced. These specifications should include all aspects of each material being used in the system, down to, for example, the formulation of sealants and desiccant materials and the expectations of the completed IG unit assembly and application and all added value in between. This process should be lead by the IG manufacturers but should include the supply chain and customers. This process can utilize tools such as FMEA (mentioned above), may require testing, etc. The outcome of this process is documentation that will provide the definition of the intended product; the starting point. It is from this definition we can start to define variation in materials, design and process and their effect on failure and overall IG unit durability as well as quality processes designed to control, eliminate or detect variation. For the small manufacturers assembling a purchased a system, much of the specification will come from the supply chain and with it an understanding of the materials and their interactions and effects on durability. Component quality assurance processes and validation testing should be provided and documented; deepening understanding of the materials, accompanying recommendations for application, handling and storage requirements. Some examples of items which should be included in an IG specification are:

- Material specifications including required, relevant material properties and their acceptable variances are required. This includes formulation requirements if material properties are dependent on formulation variances and additive changes.
- Material handling and storage requirements are necessary and can be provided as part of the material specification or general are presented in the process specifications. The materials and the expected material interfaces in IG products are susceptible to many types of contamination air born moisture (liquid and vapor), dust, etc., human body oils from finger prints, safety and handling equipment such as gloves, hand lotions, etc.
- Design attributes such as geometries and position of the spacer systems and their acceptable variances. Generally, this design and process information is efficiently presented in component part and assembly drawings. These should include consideration of process attributes such as burrs from cutting processes, which can interrupt sealing interfaces.
- For each requirement a metric of success, definition of failure and an expected corrective action should be documented. These lead to defining efficient quality assurance processes.
- Performance based testing requirements which may range from the raw material level of the IG components to the completed systems level testing including ASTM and other industry, certification, energy and durability testing requirements.

Quality Improvements

Beginning with a well defined IG product and expectations of performance, IG unit durability can be evaluated and the effects of variation and application considered. One of the major challenges of evaluating root cause failure in IG unit systems has been working past detected quality issues. Laboratory data supports that a large majority of failed IG units are due to quality related issues. This is also a general attribute of infant product failures. The number one effort for improving current IG unit durability lies in improving quality. This includes raw material quality such as reducing variation in material properties, component processing quality such as proper glass cutting and cleaning, spacer fabrication, etc. and final assembly and unit sealing. There are several quality processes and tools offered through industrial and quality organizations that support defining and implementing quality assurance processes. Many of these organizations as well as supply partners and consulting firms offer on-sight support.

Just as the supply chain is an important partner in delivering to the manufacturing and specification processes, they are also important in delivering to the quality process. The communication flow up and down the supply chain, as presented in Supply Chain Management (SCM) Methodology Tools, must carry requirements that any change, including change in expected or planned variation, must be evaluated throughout the supply chain as to its possible effect on all aspects of the final product expectation.



Supply Chain Management (SCM) Communication and Participation

This requires that all partners in the chain participate in developing (specifying), understanding and monitoring the requirements of their products as they relate to the completed, more complex system. The complex system specifications (product specifications) will include the overall statement of expected product durability; a statement that includes, for example, expectations of energy and aesthetic performance throughout the IG unit's expected life. The required and designed response of each component and material, as documented in the specification, through their respective properties and in consideration of expected variance, work together to meet those expectations. Supply chain management and collaboration become an integral part in meeting quality requirements and expectations of durability over time.

Together, a well defined and understood product / process specification and consistent quality IG unit production will reduce current failure rates, support the development of new technologies and reduce manufacturing, building and energy costs.

Durability Simulation Tool Development

Upon successfully addressing quality and diminishing the infant failure rates, we consider long term IG unit durability. Whether a durable IG unit is defined to function for 10 years, 20 years or beyond, these time frames create a challenge in validating continued IG unit durability improvements. With the introduction of new and innovative IG technologies, it has become increasingly important to rely on current and developing computer modeling and analysis and accelerated physical testing to evaluate IG unit durability. Yet, there are several aspects of testing which the project has considered and has led to the following recommendations and initial development of a state-of-the-art IG unit durability computer modeling tool.

While developing the Fault Tree Diagrams discussed above and analysis of root causes of failure, the IG unit was considered a mechanical system. In essence, the materials and the system are defined around their strengths represented by material properties, these are then are compared to the stress inputs. Where the stress becomes larger than the ability of the material strength to handle it, failure will occur. This methodology lends itself to the development of a set of stress vs. strength mathematical models. The models are coupled through their common variables. The material properties (strengths) and their variances are input distributions and are compared to the stress distributions defined by the environment and application conditions of the IG unit. As simple as an IG system may seem, when considering the IG materials and their interaction while distributing a variety of stress and strain responses to a complex set of inputs, modeling the system is not a trivial matter. Thus, the use of advancing computer technology along with the Fault Tree Diagram's natural presentation of analysis and computational flow, led to the development of a computer based durability model. The IG durability computer model, SealSim, is the first model of its kind and promises a true advancement in not only supporting IG unit development but also other building components.

The model is envisioned to ultimately be a predictive model, utilizing Monte Carlo methods to statistically choose and compare the stress and strength distributions. The current release is the foundation of that vision. The current release is a time based model which steps through the life of an IG unit comparing a set of user defined strengths (the failure criteria) with the stress input from environmental data files which can, depending on the user definitions, include temperature, pressure, wind, etc. Cautions must be given to the model’s current usage. As is the case in many developments of this type, the model needs further evaluation, has been simplified in many areas, at many levels and has yet to be validated with laboratory or field data. Yet, using the documentation detailed in this report and the SealSim Users manual, the tool can give general direction while comparing one IG unit to another. For example, IG design 1, with desiccant A can be compared through a durability index number to IG design 1, with desiccant B. The program outputs the durability index number for the first design (desiccant A) and a second durability index for desiccant B, from the two separate analysis runs. This output will guide the designer to the desiccant that outputs the higher index number, and theoretically the more durable IG assembly based on the desiccant choices analyzed. The user must input specific and accurate material properties, and ideally distributions representing property variance expected in controlled manufacturing. This general scenario in comparative analysis can also be applied to the development of the desiccant formulation itself. The current release should only be used by experience individuals with a strong depth and breadth in materials, IG design and development, mathematical modeling, program development, etc.

The durability tool also provides an opportunity to evaluate of current physical testing protocols and procedures. Current accelerated physical testing is the most common tool used to validate IG unit design and process assembly and is a requirement for industrial certifications along with computer modeling of energy performance. Physical testing and current computer modeling has helped create the current state of IG products. We expect the current testing procedures to model the environment that an IG unit would see throughout its life. Stated another way, the tests should perturb the root cause failure modes in the same way we would expect in the real life application. Defining the stress distributions which model the test environment would be a first step in evaluating the use of the durability tool for this comparative analysis. Thus the real environmental stress inputs expected over the life of an IG unit were compared to the designed conditions (laboratory stress inputs) of the testing environment and the energy modeling tools. This evaluation identified opportunities in advancing assumptions and procedures used in current IG modeling and test evaluations.

The current release of the durability tool program leverages current computer modeling tools (WINDOW, THERM, etc.) widely used in the industry while supporting the energy certification processes. Yet, to evaluate root case failure, the durability tool must extend analysis beyond the current tools and include, for example, direct and indirect radiant heat absorption of the seal components. Thus, the tool must model all the components during all environmental cycles and expected applications. For example, the current tools output validated temperature gradients from a simulated winter night. The seal temperatures which might be extrapolated from these simulations differ greatly from the seal temperatures which will be achieved during a sunny winter day with similar exterior and interior temperatures.

Figure B, presents field temperatures of two glass surfaces along with the air gap temperature for a two day interval. On a sunny day the glass surface temperatures and the air temperature reach approximately 30° C. In Figure C, the temperatures of the bottom seal materials for the same IG unit are presented. These materials reach temperatures of approximately 50° C. The field data show that the temperatures experienced by the seal can be significantly higher when the direct radiation components are considered.

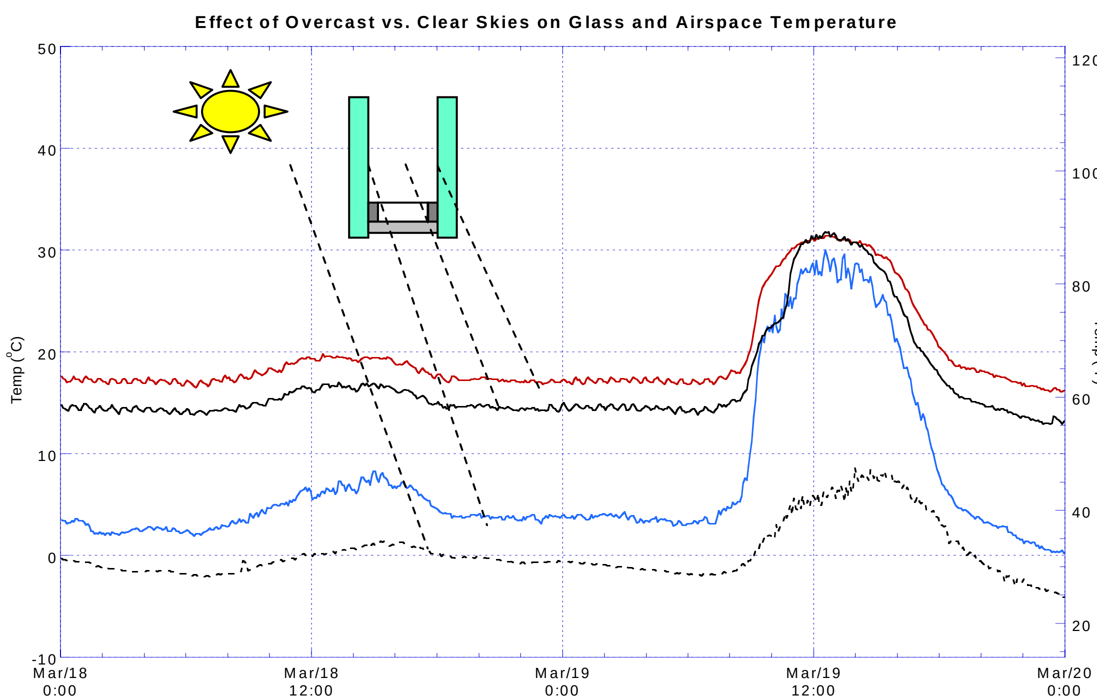


Figure B, Glass and Air Space Temperature on a Cloudy and a Clear Day. Outdoor Temperature is included for reference.

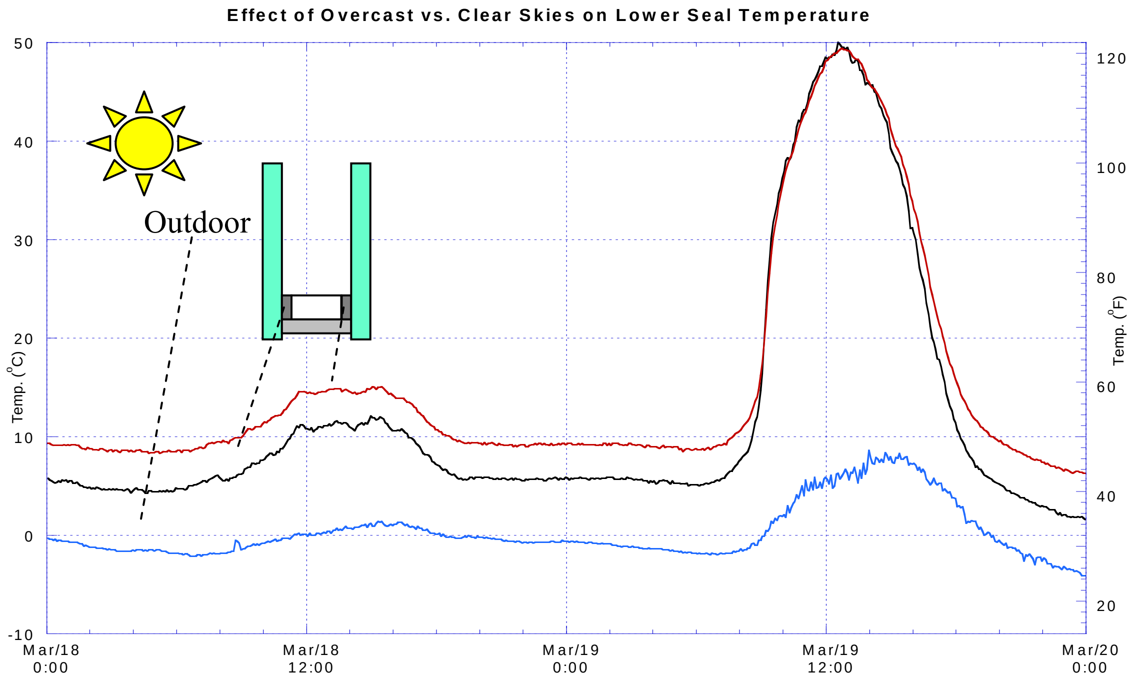


Figure C, The Influence of Solar Radiation on PIB Seal Temperature at the IG Unit Bottom Edge. Outdoor temperature is added for reference.

In addition, the same data set indicates that significant variation in temperature can exist in an IG unit at a given time as the temperature gradients cycle around the unit with the position of the sun as presented in Figure D. Accurate estimation of temperatures is important in estimating the service life of an IG unit because the permeation properties of the sealants change with temperature and stresses that can be induced by thermal expansion of the IG unit components.

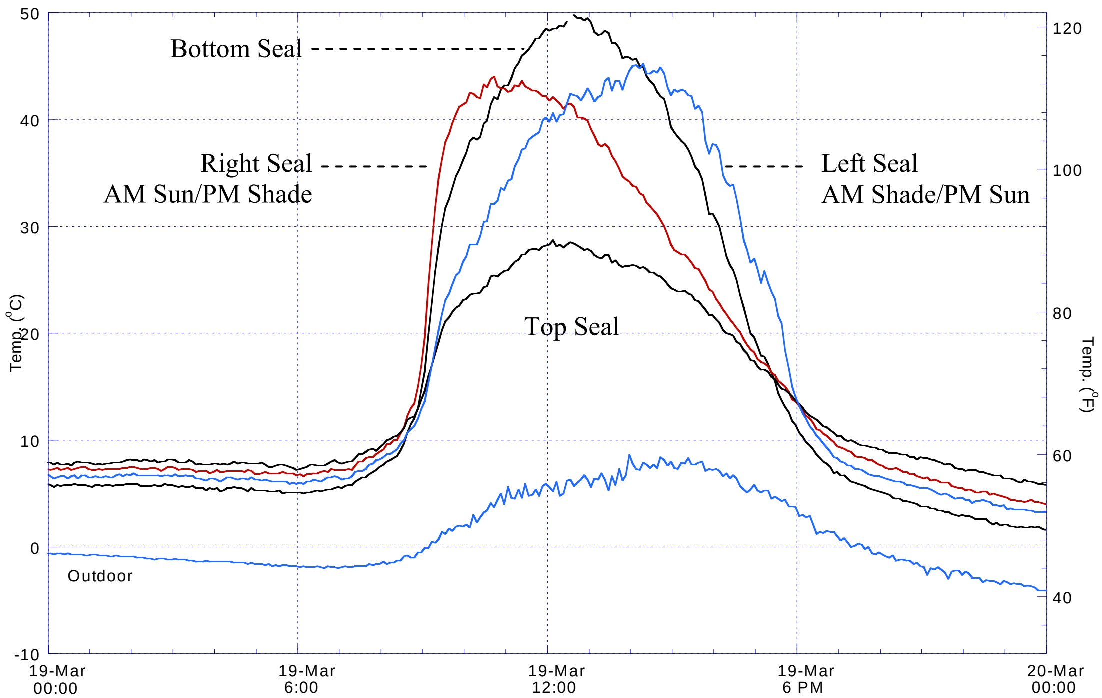


Figure D, the Influence of Solar Radiation on Seal Temperature Exterior PIB Seal Temperatures measured at the midpoint of each side

If the seal temperatures are assumed to be equal to the glass temperatures, an average of a set of temperatures or without consideration of the heat absorption component, as shown above, these types of assumptions can easily lead to 20ºC temperature error on a sunny day. This will lead to errors in calculation of thermal expansions and permeation. The permeation limitation can be overcome by providing the Durability Design Tool with a file of seal temperature as a function of time to use in the simulation.

Although high level correlation with current testing procedure continues to support validation and quality processes, advancing test procedure to consider the cycling effects and ensure the simulation of the dynamic heat gradients can only advance our understanding of durability and root cause failure.

Data available from an extensive series of weather stations throughout the U.S. and in other countries was compared with current testing procedures. The expected variation(s) between the sites and the amount of data led to the development and definition of factors that begin to reduce the data such that comparisons to other weather stations and test environments can be made. As the report details, one Stress Severity Factor, the Pressure Severity Factor, combines the pressure effects from altitude, barometric pressure and temperature. The application of these combined stressors over extended periods of time and in consideration of their dynamic cycling effect act as dynamic stressors. The result sums the effect over time and assigns the Pressure Severity Factor for, let's say, applied pressure over time. Several types of severity factors can be defined.

Using the Pressure Severity Factor as the example, first, the following Figure E shows that combining pressure effects gives a more realistic picture of how the separate pressure stressors add and subtract from each other, creating maximums and minimums that would not be identified if considered separately. Good IG unit designs and test procedures should not only consider the typical variations of these stressors but also the stressor maxima as well as cycling effects and safety factors as required.

Second, the pressure stress induced on an IG unit in test protocol can be defined by its Pressure Severity Factor and compared to the real environmental factor. Figure F shows the relationship between the expected severity of the applied pressure stressors in the ASTM E2188 test and one year of service. This severity would be calculated to be .975. The severity for one year of service for an IG unit in Mimi is 0.978. Thus, in terms of just the pressure severity the test will perturb failure modes expected to be revealed during the first year of field service.

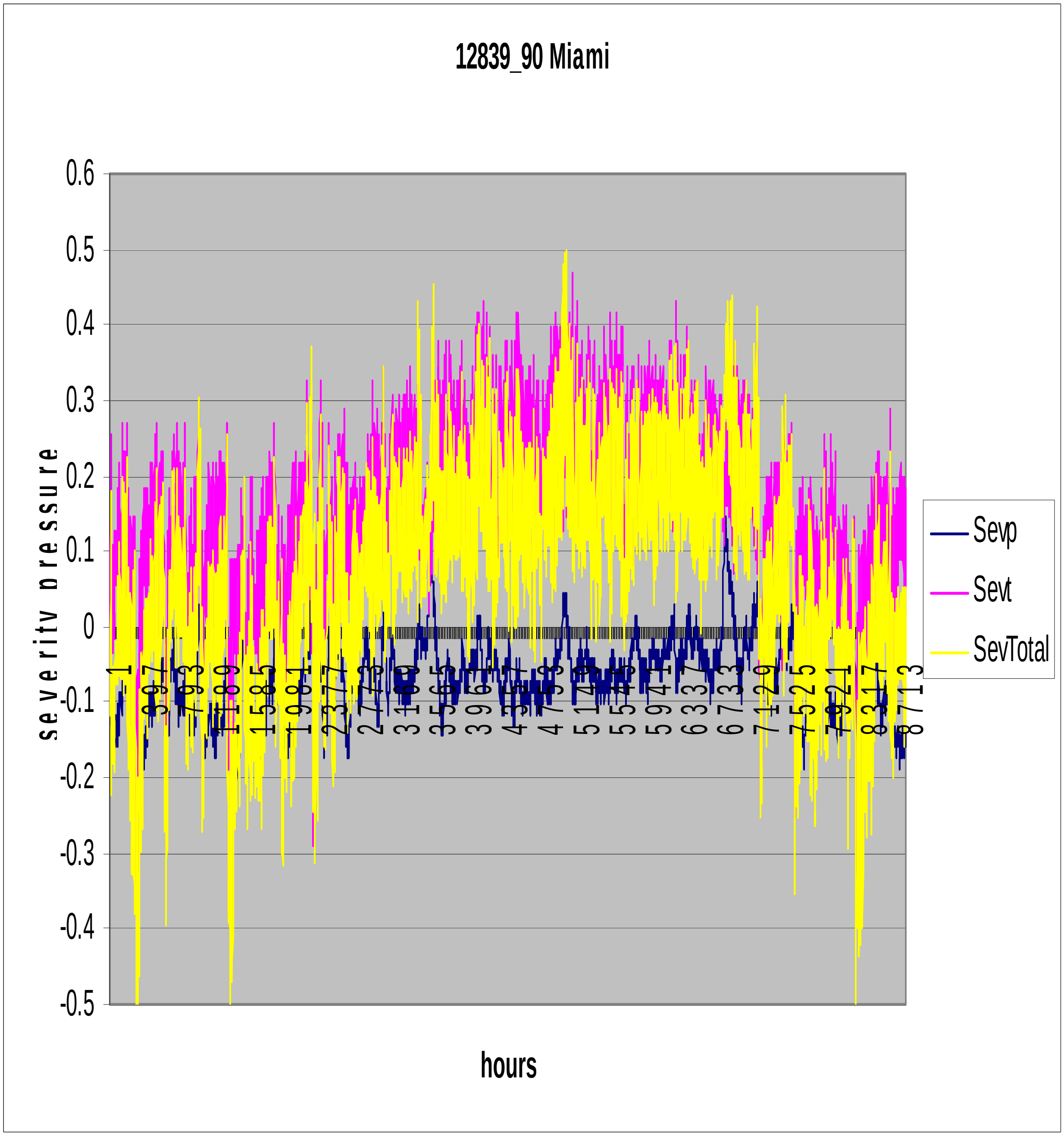


Figure E, Graph of the severity pressures from temperature and barometric pressure for the year 1990 for Miami, Florida. Total severity pressure is also shown.

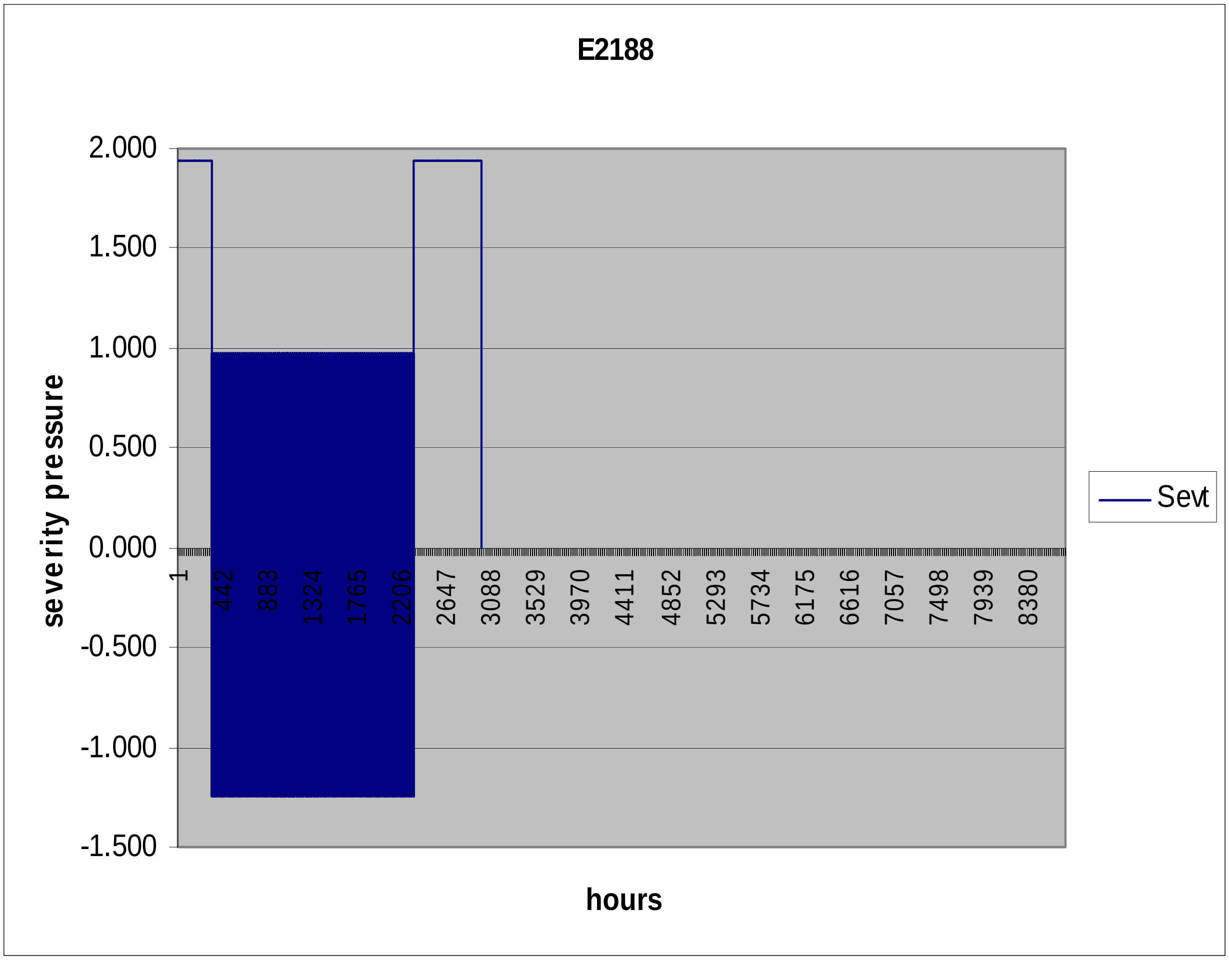


FIG. F, Graph of ASTM E 2188 test plotted on scale of 1 year total time (8760 hours). Severity pressure in psi for high humidity and cycling portions of the test with the first high humidity portion preceeding the cycling portion and the final high humidity portion following the cycling test.

Consider then, each specific year represents a specific pressure severity factor and thus other years may have higher or lower severity factors and that a severity factor, given the computational power and time, can be calculated for 10, 20 year set. In this example, the current testing would seem to provide a set of pressure stressors adequate to address, infant failures, and current field results indicate that IG units build to successfully pass these tests standards are capable of extended life, 10, 15 years. Each of the expected stressors (Heat, moisture, cyclic fatigue, etc.) would be considered in the same manner and applied to the computer model development and the advancement of test protocol and procedure.

As detailed in the report, several test developments are suggested to advance both our understanding of the modeling and IG unit development and testing. It is suggested that the advancement of the testing and the simulation tool be completed in a concurrent fashion. The computer simulation requires validation at several levels form the raw material level to the systems level. Material data is a basic requirement for the simulation and builds a fundamental understanding of the root cause failure modes which are expected to be perturbed in the test procedure. Material testing supports both test advancement as well as the model development. In the same way, system tests designed to document specific responses of the IG unit to controlled stressors support the models validation at the systems level and the development of test procedures that, when consolidated, can deliver the most efficient and value based testing in support of quality and certification.

In summary, the following recommendations are made:

- IG units should carry identification explicitly referencing a compressive product and process specification. Field data can then begin to be correlated to systematic and root cause failure. In addition, industrial processes should be defined in a collaborative manner to combine filed data with unit production and regional application.

- Disciplined quality processes which not only ensure manufacturing of consistent quality products but also ensure collaboration with the supply chain to address monitoring of material and component changes should be implemented. Change initiated through technology, business, market, etc. would then be proactively evaluated throughout the supply chain and monitored as to their effect on product and durability expectations.

- Development of comprehensive durability simulation tools should be continued, supporting condensed time frames for technology implementation, cost savings and general business opportunities for profitability.

- Consideration and evaluation of stress input and IG unit response should continue to be addressed advancing the durability simulation models as well as advancing physical testing to ensure quality and long term efficient product application.

- Physical testing protocol and procedures should be advanced with a focus on IG response and root cause failure consistent with long term fatigue cycling experienced in real life applications.

1. Introduction

Michael L. Doll

1.1 The Need for "An Insulating Glass Knowledge Base"

The objective of the Insulated Glass Durability Knowledge Base, an effort funded by the U.S. Department of Energy (Cooperative Agreement DE-FC26-01NT41258), is to provide a mechanism by which durability characteristics of current IG units can be captured in a useful and practical manner. The effort was performed by Aspen Research Corporation in conjunction with its partners in industry, academia, and government. [6]

To fulfill the goals of this project, the knowledge base consists of two primary structures: a durability evaluation tool and an IG design data repository. The durability evaluation tool was designed to support the following analyses: material sensitivity, design sensitivity, environmental sensitivity, and durability performance predictions. The design knowledge repository contains practical and useful design references: event tree diagrams for representative design classes, relevant material properties, regional environmental exposure levels, mechanistic failure models, and national and international standards relevant to IG product development and testing. [6]

The Phase I report (Appendix 1) discusses the structured methodology that was followed for development of the durability evaluation tool. The methodology represents a structured approach founded upon sound reliability and mechanistic modeling principles. This Phase II report, concluding the project, discusses model development and current progress in quantifying IG durability issues while working to prioritize and suggest on-going research. The proposed research will use the model as well as acquired field data supporting project and modeling assumptions. [6] For additional information concerning this project, refer to http://www.IGDurability.org.

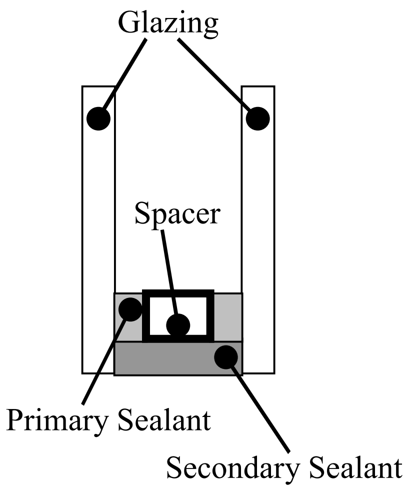
1.2 Approach

As presented in the Phase I report, this project has been defined as a two-Phase project. The first Phase discussed insulating glass durability issues at a qualitative level. That is, the relevant issues were identified, and technical understanding was developed and communicated regarding these issues. For the first Phase, the technical discussions were focused on first principles theory and practical considerations. In most cases, numeric values were not quantified for these statements, but the statements were intended to support this second Phase, the quantification of the first principles derived theory. This section discusses the overall approach taken to fulfill the requirements of this project. [6]

One of the principal challenges of this reliability effort is development of durability assessments that are applicable to a wide variety of products. In addition to variations of material properties, significant design variations for different classes of products must also be addressed. [6]

For example, two significantly different IG designs are shown below [1]. Figure 1-1 shows a common IG design, which involves a structural spacer, a primary sealant material, and a secondary sealant material. This schematic is a simplistic representation of this common IG design. The implementation of the design typically involves metals or polymers for the spacer. Another common IG design is shown in Figure 1-2. This design uses the sealants as the spacer. In both designs, the primary and secondary sealants are typically some of the following organic compounds: butyl (hot melt or not), polyurethane, polysulfide, or silicone [2]. In addition to various classes of materials being used, there are also significant variations within the material classes due to formulation differences. When comparing these two designs, it is obvious that their durability response characteristic will not, in general, be identical. Rather, their failure mechanisms may differ substantially. [6]

Failure Modes and Effects Analysis (FMEA) is the recommended approach that will be used to capture understanding of how the failure mechanisms relate to system failure. The FMEA documents form the initial basis for considering the durability similarities and differences between differing designs. [6]



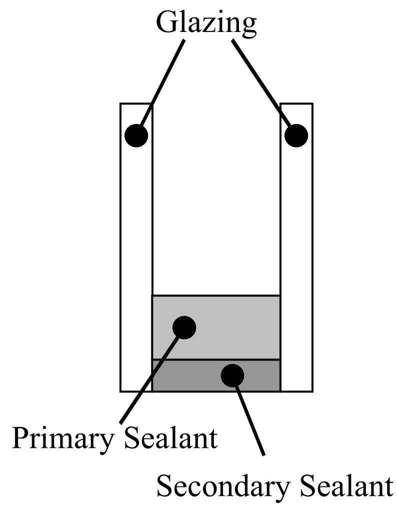


Figure 1-1 Common IG design with box spacer **Figure 1-2. Alternative IG design**

Event tree diagrams were used as a tool to translate the verbal FMEA descriptions into mathematical constructs to describe system failure. The event tree approach is commonly used to capture the interaction of failure mechanisms for complex systems [3]. The event tree begins at the top level as a system that has not yet experienced failure. Paths from the initial state then progress along tracks of sub-system failure events until the end system result of either failure or success (non-failure) is achieved. [6]

As discussed in the Phase I report, the event tree diagram must be developed uniquely for each identified class of design. An example event tree diagram, developed for the case of an IG with spacer design (represented in Figure 1-1) is shown in Figure1-3. This event tree diagram is for illustration purposes only, and is not, by any means, intended as an official finalized diagram for describing this design’s potential failures. [6]

The event tree shown in Figure 1-3 begins with the state of a non-failed IG unit that has just begun its service life. Its durability performance over its expected service life is then modeled as a chain of potential failure events. Each link in the chain of potential failure events can be modeled as a flowchart decision block with the outcome of the event being either success or failure with respect to the stated mechanism. If the block fails due to its stated failure mechanism, the continuing failure chain is then evaluated to ascertain whether the chain of events will continue until system failure is realized. If failure does not occur, other failure mechanism chains are examined to see if they will result in failure. The flow continues until either system success or failure is ultimately realized. [6]

The decision blocks in the event trees were intended to be developed such that they each capture a unique failure mechanism, such as primary seal cohesive failure or primary seal adhesive failure. At this point it is important to develop a methodology for consistently assessing the individual decision blocks. To evaluate the decision blocks it is necessary to think of each potential failure in terms of the competing nature of stress and strength. The completed event trees will not only incorporate field induced stresses, but will also incorporate stresses and thus failure events corresponding to processing issues. The general methodology originally intended to treat each of the decision blocks is described in Figure 1-4, for the specific case of primary seal cohesive failure. [6]

As is seen in the Figure, in order to evaluate the outcome of the decision block it is necessary to have the following four primary elements:

Relevant environmental parameter values
Relevant material property values
A translating algorithm for converting environmental parameters to material stresses
An algorithm for comparing the material stress values to its strength properties

To be the most useful, the environmental stress and material property data should capture not only the expected values of parameters, but also their probabilistically distributed nature. The translation step will involve mechanistic modeling of the failure mechanism in terms of the environmental stress. The outcome of the decision block will be a result based on the comparison of the translated stress and the defined material strength. [6]

The envisioned procedure for evaluating event tree diagram decision blocks would be implemented in a consistent manner for each decision block, which is shown in Figure 1-5. When applied in such a consistent manner, the result would be two algorithms that are defined within each decision block: the environment to stress translation algorithm, and the stress to strength comparator algorithm. The stress translation algorithms, each unique to a design block, would draw data from the environmental database. Each translation algorithm would draw the environmental parameters from the environmental databases, which are relevant to the mechanistic model [4]. The comparator algorithms would also be unique within each decision block. The comparators will draw material properties from the material property database, which are relevant for the material and stress value under consideration [5]. The environmental database will include information of all relevant environmental parameters and for all relevant environmental regions. The material property database will include information on all relevant material properties and parameters. The ideal environmental data and material property data will be stored in terms of not only expected values, but also in terms of the probabilistic nature of the parameter values. [6]

When the event tree diagrams are completed, with their embedded decision blocks and mechanistic models, they will then be evaluated. The event tree is driven by probabilistic events, due to variation in environmental stresses and due to variation in material property strengths. The system would thus be assessed by treating it as a stochastic process. [6]

A variety of techniques can be used to develop durability statements from the resulting system model relationships. In the Phase I effort, statements were made using a model with relatively few system failure mode blocks. This more simplistic representation provides some initial insight into perceived IG durability performance. [6]

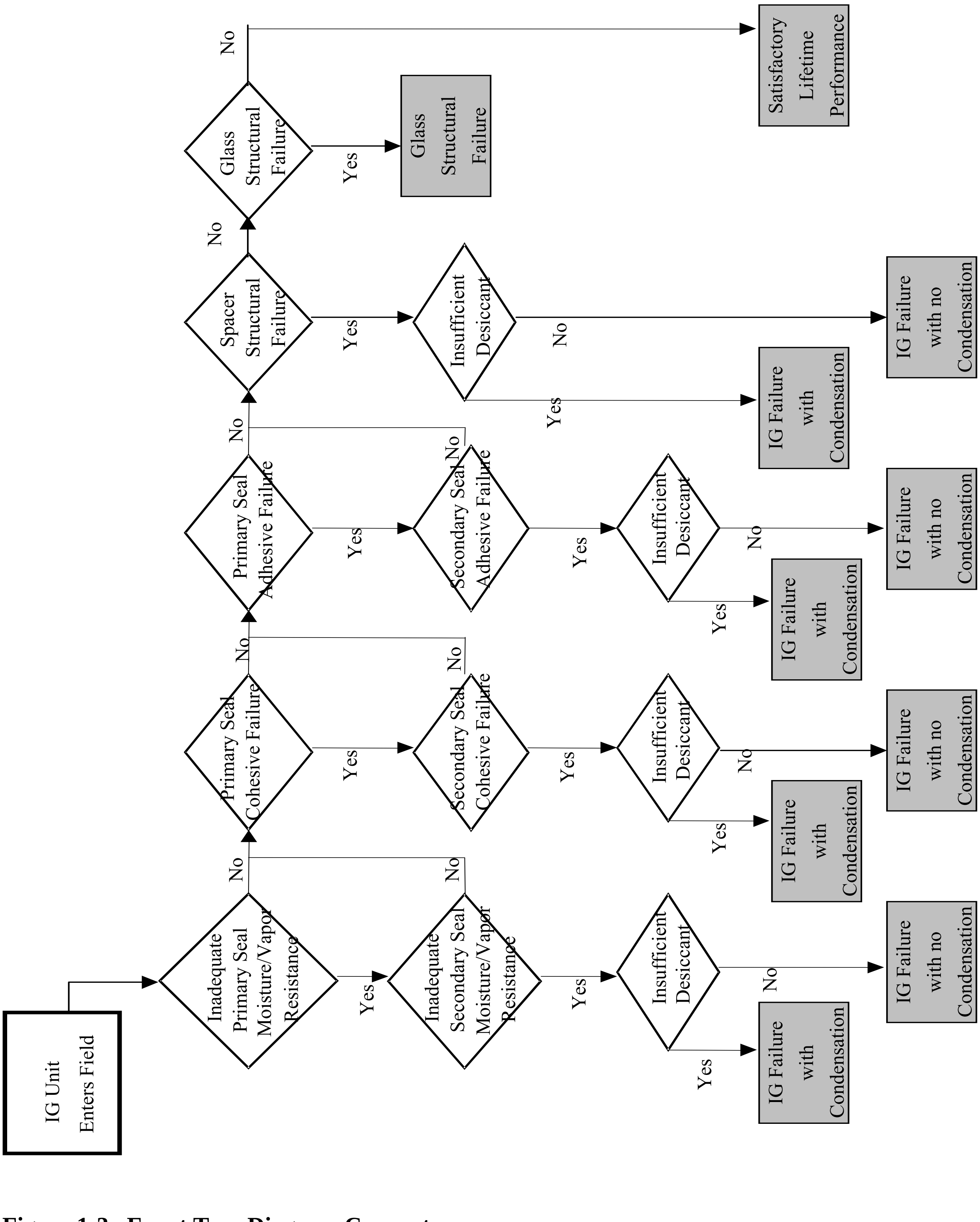


Figure 1-3. Event Tree Diagram Concept

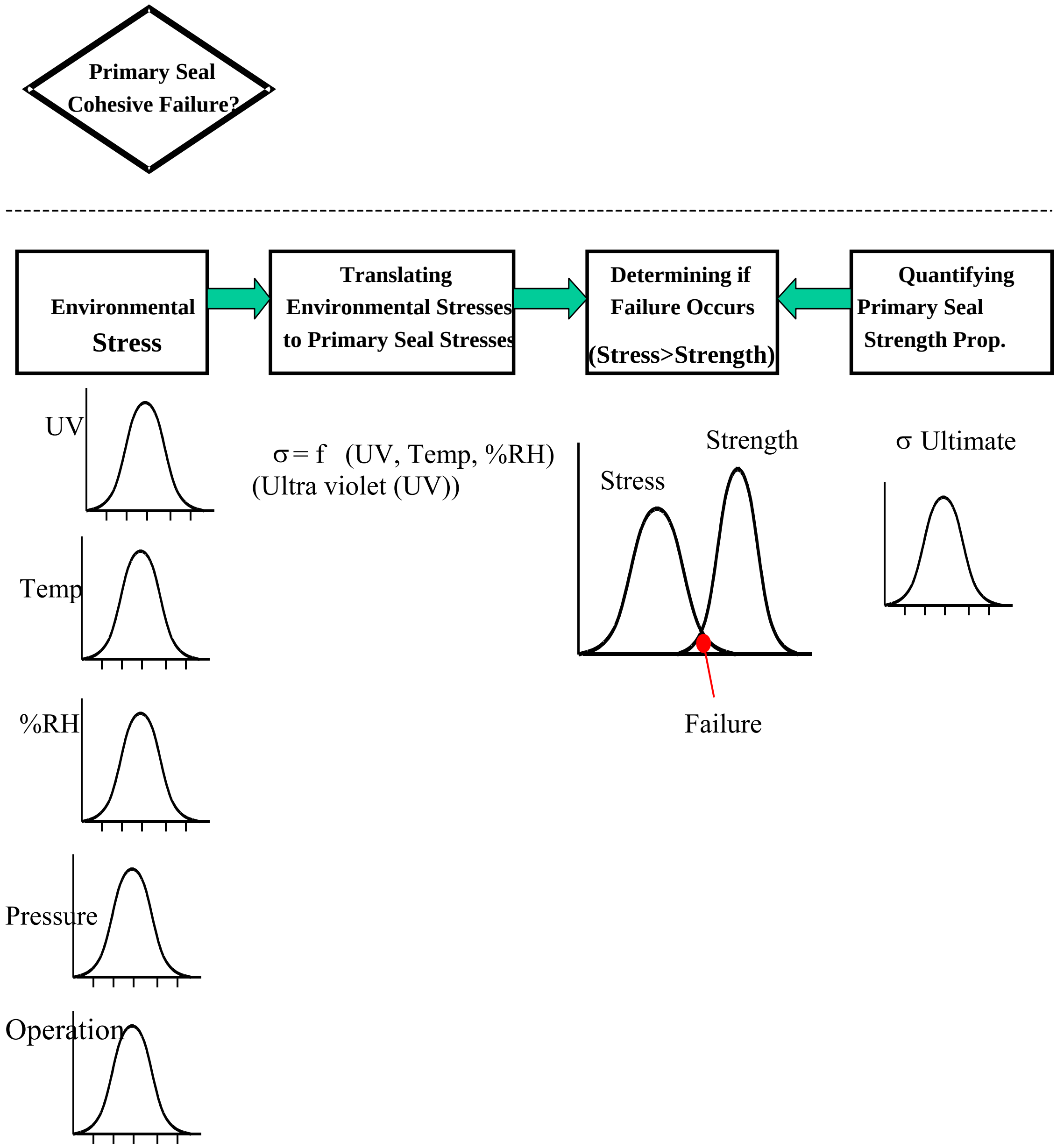


Figure1-4 Recommended Methodology for Evaluating Event Tree Blocks

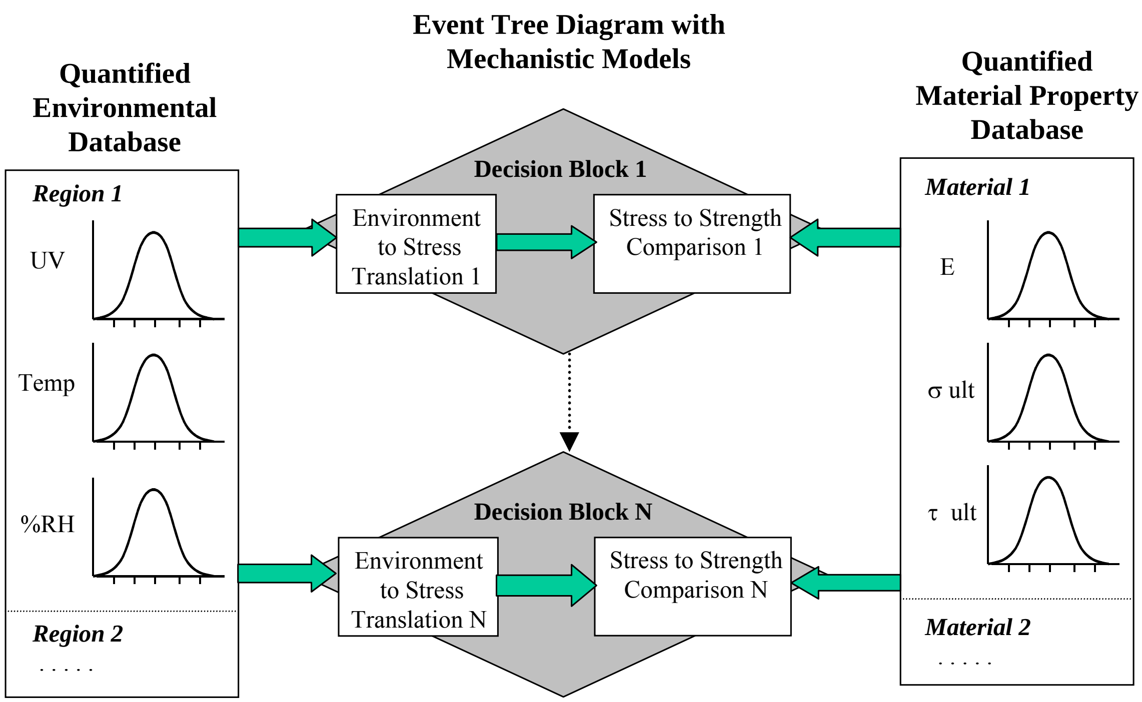


Figure 1-5. Generic Flow of Data for the Knowledge Base

The complete validated outcome of this effort would be a structured tool for IG durability evaluation. The tool will be useful for the following activities. [6]

Material sensitivity analyses

Design sensitivity analyses

Environmental sensitivity analyses

Durability performance predictions for stated designs

This structured approach will result in the development of unique event tree diagrams for each class of IG design. The FMEA's generated will provide useful templates for understanding and guiding IG and spacer system design and production processes. Within each of these designs, inherent material and environmental variations dictate that a probabilistic approach be utilized. The necessity of converting environmental parameters into material stresses dictates that mechanistic failure models be developed and implemented. [6]

The structured approach resulted in a practical and meaningful IG design data repository. The following IG design knowledge was captured:

Failure Modes and Effects Analysis document for each IG design class
Event tree diagrams for each IG design class
Material properties for all relevant generic and specific IG material properties
Relevant environmental exposure values
Mechanistic models (translation algorithms) for defining material stress in terms of environmental parameters
National and International standards for IG product development and testing (The current project focused on North American and European standards documentation)

If one were to rigorously follow this methodology, it would be assured that all relevant failure mechanisms, environmental parameters, and material properties are addressed. In addition, interactions between the failure mechanisms would be captured and understood. In summary, following this structured approach will ensure that a useful and practical durability evaluation tool for the Insulated Glass Durability Knowledge Base is achieved. [6]

As the methodology described above was implemented, it became obvious that the final goal was optimistic within the time and budget constraints defined within the project. As a first step, work proceeded on a time-based approach model rather than a program flow developed around following the probabilistic fault sequence of events. (Fault tree diagrams). Succeeding in this scaled-back effort produced the foundation of the originally envisioned model. Future efforts can then build on this foundation for full implementation in modeling the fault tree diagrams. The scaled-back model will not produce results which can directly advance system design relative to probability of an identified root cause and subsequent chain of events leading to failure. However, its immediate and important advantage is that it has successfully coupled fundamental mathematical models of stress with permeation. Instead of the fault tree diagram as the model for program flow, Figure 1.6 presents the program flow of the time step approach.

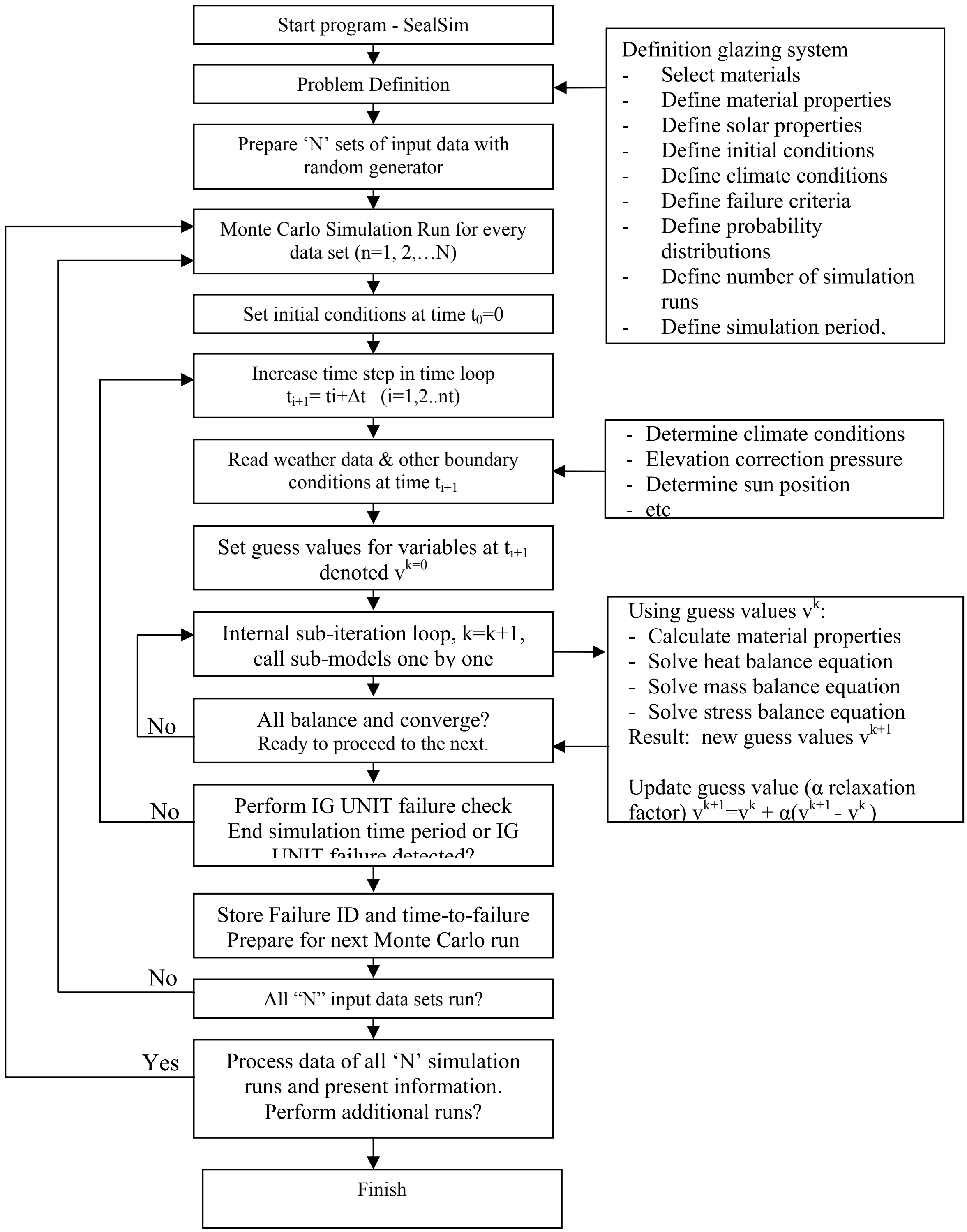


Figure 1-6. Generic Flow of first vision, IG durability simulation model [7]

As can be seen in the Figure 1-6, each of the sub models is addressed as each time step is initiated with its unique set of initial conditions rather than a program flow that follows a path of computation based on the outcome of the decision block before, Figure 1-3. This time-step-simulation models the system as a whole through simultaneously solving the coupled differential equations which represent the whole of the fundamental system response to the induced stressors, as in real time, resulting in outputs which will provide direction and support for prioritization and continuing research addressing:

Material sensitivity analyses to advance IG material selection and application including required bulk properties and their appropriate specifications as they relate to IG durability and the effects of process variation on IG durability

IG design analysis for current and future innovations leading to design choices that enhance IG durability using design sensitivity analyses

The induced stress effects, including magnitudes, cyclic fatigue, gradients, etc., leading to appropriate design specifications using environmental sensitivity analyses

Durability performance predictions for stated designs

In addition, in the hands of experienced researchers, engineers and designers, the simulation tool will provide direction and insight to address issues which can have immediate impact on IG durability.

This Phase II presentation continues to leverage off the Phase I activity, which was primarily involved with development of first principles qualitative understanding of IG durability. This Phase II effort focuses on quantification.

1.3 Content of the Phase II Report

This report is a comprehensive presentation of the project from discussion around the original proposal through the concluding tasks and will discuss the relevant issues by presenting the developed Phase II conclusions in a logical format. This report is intended to disseminate information, data, hypotheses, instruction, conclusion, suggestion etc. in a form and vocabulary that is understood and usable for the general designer and / or engineer. A major portion of this project deliverable is a computer based IG durability simulation program. The long term implementation plan for this simulation program continues to be directed at the IG or fenestration designer. However, as will be presented, the current version of the simulation program is useful in the hands of a group or individual with a great deal of depth and breadth of experience in all associated areas of science, engineering, computer code, mathematical modeling, etc. This current program is the first simulation program of its kind and this version will provide output that is and will be very beneficial in understanding IG durability and IG durability opportunities.

Included in the report and its appendices are presentations of data that in some cases, in its original presentation, was defined as sensitive to or by its contributors. These contributors have provided this data in support of advancing the industry as well as support of the energy goals and objectives of the United States Department of Energy. This data has been sanitized and when requested, there will be no reference to those contributors except at a high level (i.e. provided by the industry supply chain). In some cases permissions were granted identifying the specific contributor. Contributors may not be listed based on their request.

Chapters 1 and 2 will present an overview of the project proposal, Phase I and Phase II project plans and activities. In addition, acquired data will be discussed relative to project assumptions.

Chapter 3 provides initial definition and statements of durability. From this discussion, the development of the durability simulation tool is presented. The presentation addresses the fundamental mathematical algorithms, coupling, the graphical user interface, database construction and use, assumptions, etc. including a sample analysis discussion. As each element of the IG system is addressed in the model discussion, consequences of process, quality and design are addressed. Data suggesting validation as well as supporting continued development is discussed. In addition, the simulation program's compatibility and use with current energy / fenestration modeling tools is discussed along with suggestions and direction for continuing advancement of the tool's capabilities and probable integration.

Chapter 4 presents material on increased understanding of IG performance derived from available data and the simulation tool intended to support discussion and focus around evaluation and suggested advancement of the current IG physical testing procedures. This discussion considers development and theory of accelerated testing and how it is currently applied in IG testing, consideration of the stress applied to the IG as supported by environmental data and acquired field testing data and how these are currently addressed in test procedures. The discussion continues with suggestions to improve the procedures.

Chapter 5 summarizes the project by way of discussing suggested future activity based on our stated conclusions. The presentation is intended to address both short term opportunities such as process and quality and longer term research such as needs for continuing development of the simulation tool, test protocol, data collection and durability validation.

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2. Experimental - The Need, Proposal & Project Plan

"An Insulating Glass Knowledge Base"

Michael L. Doll

2.1 Original Proposal

There are several relevant and timely issues which were presented in the original project proposal. A plan of action was developed by a team representing industry and headed by the Department of Energy. This team identified the need and defined the overall approach to create and maintain an insulating glass (IG) knowledge base or repository of IG knowledge and information. The following is a paraphrased presentation of selected sections of the original project proposal with the addition of supporting data around the original assumptions which were used to begin quantifying the IG durability opportunity.

Need/Problem Definition

Recent results from studies on Insulating Glass panels indicate that the energy efficiency of the United States' population of aging windows is degrading. In addition, recently settled lawsuits filed by homeowners over massive failures of IG units ranging from fogging to loss of argon gas have brought the issue of IG durability to the forefront. A few manufacturers stand behind their products with 20 year warranties, but most have either no warranty or at best 5 years, and the homeowner usually doesn't know what warranty they have. These failures result in losses for the homeowner or the manufacturer depending on the agreed upon warranty. In any case, society experiences loss in energy efficiency and from the time wasted and energy spent manufacturing replacement IG panels that are likely to fail again.

The Window Industry Technology Roadmap, sponsored by the U.S. Department of Energy's Office of Building, State, and Community Programs, identified durability of windows as being a barrier to the advancement of the product. The subgroup identified three actions to overcome this barrier, they are:

Establish a system for rating products on the basis of durability.

Define appropriate durability and warranty periods for different window components.

Develop products that encourage consumers to upgrade as features advance.

This project covers the first two of these issues developing a public domain knowledge base, which could be used by standards organizations to create consensus standards that directly affect IG unit durability.

Insulating Glass (IG) panels have been a part of residential housing for almost 35 years. They now account for approximately 90% of all new construction windows sold in the United States.

The first double glazed IG unit, featuring clear glass on both lites along with a thermal break in the spacer, was first introduced in 1965. Its popularity increased largely because of the energy crisis of the 1970's. Dual lite glass units improve the performance by creating a pocket of air through which heat needed to diffuse. Just by including the extra lite of glass, the U-value of an aluminum framed window dropped from 1.25 Btu/hr ft^2 °F to 0.79 (1) and the solar heat gain coefficient was reduced from 0.76 to 0.68. In this case, the simple inclusion of an extra lite of glass reduced the energy drain due to windows by approximately 37%.

The next invention to significantly affect the energy performance of existing homes occurred in single stack spectrally selective coated glass. Bronze-coated glass succeeded in reducing the U-value to 0.49 and the solar heat gain coefficient to 0.46. Later, when silver deposited in metal oxide "sandwich" coatings were used, these values were reduced even further. Today an IG panel with double stack silver oxide coated glass has a typical U-value of 0.35 and a solar heat gain coefficient of 0.31 (Window 4.1).

Upon the introduction of argon and krypton gas used to fill the insulated glass unit instead of air, the U-value fell to 0.31 and the solar heat gain to 0.29 (Window 4.1). The downward trend here was achieved largely because the reduced thermal conductivity of the noble gases coupled with their higher viscosity led to a reduction in both normal conduction and natural convection.

A recent update of an IG durability study by the Sealed Insulating Glass Manufacturers Association (SG2000-90 – Results of SIGMA 10-Year Field Correlation Study), showed that after 10 years in the field, 10% of the units had failed. The U-values of these units had degraded from approximately 0.3 to 0.6 while solar heat gain coefficient changed from about 0.3 to 0.7. This means that if the units were argon gas filled with spectrally selective coatings on the glass (U-values / SHGC, 0.3 / 0.3), the IG panels have degraded to the point where they are performing like clear glass, air filled IG panels (U-values / SHGC, 0.6 / 0.7) effectively negating any gains that were made by argon gas filling or spectrally selective coatings on the glass.

Recently, the window and glass industry has become aware of another problem associated with the insulated glass units. Over time, the primary polyisobutylene (PIB) seal weakens and breaks, allowing the argon fill to diffuse out. Since argon diffuses through silicone three times faster than air diffuses inward, the IG panel collapses from the net molar loss of gas. The scope of the problem is still not fully understood.

These issues have left the glass industry poised to retreat from its present design and exclude argon or krypton from any new product offerings. This would lead to an increase in U-values, and a subsequent loss in energy efficiency. Moreover, the entire concept of a double lite, dual seal insulated glass unit is in jeopardy of being discredited.

Description of the Technology

To understand IG unit durability, it will be necessary to combine knowledge of failure mechanisms with observed failure statistics. Knowledge of either failure mechanisms or failure statistics alone would be insufficient for our proposed goal. Knowledge of failure statistics is insufficient alone because although it does capture the product's variability in the field, it does not capture physical knowledge of how the failure mechanisms respond to their environment. Knowledge of failure mechanisms alone is insufficient because it will inadequately capture observed variation in the field. Knowledge of failure variability and failure mechanisms thus must both be captured in our analysis in order for the goals to be successfully achieved. Previous efforts using only statistical techniques (2) resulted in statistical estimations for a particular type of product in a particular region with no quantified understanding of the systems response to changes in either the environmental factors or design factors. The insulating glass knowledge base, which is the subject of this report, will overcome previous shortcomings by addressing the underlying failure mechanisms while considering the failure statistics, thus allowing assessment of IG unit durability for varying designs and environments. Reliability theory will provide the means by which the failure mechanism physics will be combined with observed variability.

All of the efforts in this project include a consideration of a wide typical range of IG product designs. The project has progressed in the following steps. First, a team of industry experts was convened for the purpose of defining what an IG failure means in quantifiable terms. The failure definitions took into account the amount of energy loss due to both product performance degradations and loss of confidence of consumers in the product. Second, a Failure Mode and Effects Analysis (FMEA) were performed to determine the relevant modes by which the defined failure can occur. The resulting FMEA will support construction of a system diagram which represents the relationships of individual failure modes to overall IG unit performance (3). At this point, the durability of existing systems can be quantified by incorporating observed field failure statistical distributions of the individual failure modes into the system model. The durability assessment methodology developed as well as the quantified durability estimates of representative products were input into the Knowledge Base.

The next step of the effort was a detailed evaluation of the failure modes identified in the FMEA. The failure modes were evaluated quantitatively with the goal of developing mechanistic models which express the failure modes as a function of their environment and their inherent resistance to their environment. Analysis of the failure modes results in a thorough understanding of the underlying failure mechanism. An example of an identified failure mode would be an IG unit with the failure mode of the primary seal releasing at the panel's corner. The failure mechanism for this failure mode would be the exact chain of events leading up to the failure. The quantitative mechanistic-based failure model of this failure mechanism would be a numerical relationship which would express time-to-failure in terms of the quantifiable magnitude of its thermo-mechanical environment and its inherent strength properties. The mechanistic models of the individual failure modes would be evaluated either empirically or through direct mathematical development of physics based failure model. Examples of such physics-based models used successfully in the past are the Arrhenius model and the Eyring model (4). Both models provide a mathematical representation of the time to failure of a system in terms of its strength and the stresses it observes. The Arrhenius models micro-electronic failures in terms of its stress temperature. The Eyring model is used for a more general class of components but also uses temperature as its driving variable. Data can then be generated from system and subsystem level testing which appropriately stresses the identified IG failure modes and may be used to determine such quantitative mechanistic failure relationships for IG units. The input to the Knowledge Base would be a verbal description of the failure modes and their underlying mechanisms, as well as mechanistic models for describing the times-to-failure of the failure modes in terms of the failure mechanisms.

With the failure mechanisms of the individual failure modes adequately understood, the next step is incorporating the quantitative mechanistic failure mode models into an overall

IG unit durability model. This is accomplished by including the mechanistic failure mode models into an overall system model consistent with Failure Modes and Effects Analysis derived relationships. The resulting quantitative mechanistic-based system model can then be used for prediction of product performance. The output performance predicted would include spacing and energy efficiency or other identified failure measure as a function of time. By coupling the time responses of the performance outputs with the failure criteria, we can then determine the IG unit durability over a given operation time.

The resulting prediction tool provides an estimation of IG unit durability given the inputs of IG unit design defining parameters and environmental parameters. The IG unit design-defining parameters would include material and design characteristics such as design styles, length and width of the unit, and the glass thickness. The IG unit environmental parameters would include measures of the units' environment such as thermal conditions. The resulting prediction tool could serve as a template for use by IG designers to allow appropriate specification of future IG units given their intended environment for a stated acceptable performance level. The prediction tool could also be an estimation tool for the performance of existing products in various environmental conditions; it would also be useful for design parameter and environmental factor sensitivity studies. The developed design prediction tool will be an input to the Knowledge Base.

The quantitative mechanistic failure mode and system models developed in this effort can be used for development of accelerated life tests which have a direct correlation to time durations of service exposure (4). Current accelerated tests, P1 (5) and P2 (6), accelerate the modes of failure, but they do not have direct measurable correlation to service life in the field. Thus, they only provide a qualitative rather than a quantitative measure of IG unit durability in the field. An accelerated test which is correlated to service life would be a great benefit as it would allow a timely evaluation of a system's quantitative durability which could be used to establish a product rating and warranty period determination. The design prediction could be used as a first screen to determine which prototypes to build and the accelerated testing could be performed on the prototypes to quickly determine which units to send for field trials and ultimately to production. This rigorous methodology will yield products that are durable. This test methodology has been captured in the Knowledge Base. Public education and dissemination of this effort will support creation of effective IG panel durability standards.

This research will support the creation of a system for rating products on the basis of durability and performance and will allow determination of appropriate warranty periods for new and existing IG units. The Knowledge Base developed in this effort, when coupled with historical knowledge and experience of the IG industry, should lead to the definition of an acceptable level of IG unit durability. The Knowledge Base output of this effort will also provide means of quantifying, rating, and validating IG unit durability.

Performance Improvement and Energy Savings

We propose to show the improvement in long-term energy savings that can be realized by improving the durability of IG panels. In order to make these predictions we will make assumptions about the installed base of IG and the potential new installations of IG in the United States. The basic assumption will be that after 10 years in the field, 10% of the existing IG units have failed. These failures reduce the performance of these IG units to that of uncoated, air-filled, double lite IG units. In the following analysis, we will compare the present situation with the possible situation of a more durable IG unit.

Please Note: The following calculations are based on the population of currently installed IG units. This inventory of installed IG units represents about 25% of all windows installed in the United States. For the purposes of these calculations we assume that the inventory of installed IG units does not change. This will result in a conservative estimation of energy savings since the percentage of installed IG is likely to increase over time as single glazed windows are replaced with insulated glass panels.

Using present building stock, the nation consumes 7.52 quads of energy from heating and 1.5 quads of energy from cooling. Of this, thermal conduction through windows accounts for 1.45 quads for heating and 0.01 quads for cooling. We assume that the energy load is caused by conduction through windows. Most insulated glass units are manufactured with a U-value of 0.27 Btu/hr ft^2 °F and a solar heat gain coefficient of 0.44. (.5 inch gaps, argon fill, double silver low-e coating, WINDOW 4.1) We assume that 10% of these IG units experience seal failure after 10 years of installation and that moisture and air will diffuse into the insulated glass unit. Therefore, the failed insulated glass units will have the U-value of non-argon filled IG units (0.49 Btu/hr ft^2 °F). Also, the presence of moisture and air will cause the low emissivity coatings inside the insulated glass units to oxidize and raise the solar heat gain coefficient to the value of clear glass, which is 0.58 (Window 4.1.). In 10 years of time, today's installed IG units will therefore have an average U value of:

(0.9*0.27 + 0.1*0.49) = 0.292 Btu/hr ft^2 °F

And a solar heat gain coefficient of

(0.9*0.44 + 0.1*0.58) = 0.454

In other words, the insulated glass units must suffer a 3-8% penalty due to a lack of durability. Our proposed work will insure that after 10 years, all insulated glass units will meet the industry standards.

Energy Savings

Step 1: Estimating energy savings over typical products:

Improvements in durability will increase the energy savings of new building products over a 10-year time period by preserving the original U value of 0.27 Btu/hr ft^2 °F. Hence we will save 0.022 Btu/hr ft^2 °F or approximately 8% of the energy losses due to windows. This estimate can be applied to both heating and cooling loads.

Improvements in insulated glass durability will improve the solar heat gain coefficient by 0.014 or improve the solar heat gain position by 3%.

Step 2: Residential Space Conditioning Energy Consumption

The energy savings potentials would conservatively be:
Current residential heating loads from residential windows

	Heating (Quads)	Cooling (Quads)
Conduction	1.45	0.01
Solar	-1.15	0.42
Total	0.3 Quads Heating	0.43 Quads Cooling

Assume:
25% penetration of durable insulated glass panels into present housing by replacement. This estimate is conservative since it does not address the true replacement market which primarily consists of single lite windows having U values in excess of 1.3 Btu/hr ft^2 °F.

Conduction
8% heating energy savings from conduction * 1.45Q * .25 = 0.029Q
8% cooling energy savings from conduction * 0.01Q* .25 = 0.0002Q

Solar Heat Gain
3% heating energy savings from solar heat gain * -1.15Q * .25 = -0.00863Q
3% cooling energy savings from solar heat gain * 0.42Q* .25 = 0.00315Q

Total Residential Current………………… 0.024 Quads

<u>Residential – New (i.e. next 10 years)</u>

	Heating (Q)	Cooling (Q)

Conduction	0.15	0.01
Solar	-0.12	0.11
Total	0.03 Q Heating	0.12 Cooling

Assume 95% penetration of the market.

Conduction

8% heating energy savings from conduction * 0.15Q * .95 = 0.0114Q

8% cooling energy savings from conduction * 0.01 * .95 = 0.00076Q

Solar Heat Gain

3% heating energy savings from solar heat gain * -0.12Q * .95 = -0.0034Q

3% cooling energy savings from solar heat gain * 0.11 * .95 = 0.00313Q

Total Residential New………………….. 0.012 Quads

Residential Current 0.024 Quads

Residential New 0.012 Quads

TOTAL 0.036 Quads

Assuming the generic carbon emission factor for residential space heating of 15.35 Kg/MMBtu and that cooling is all operated by electricity with a carbon emission factor of 15.67 Kg/MMBtu, this amount of energy savings would translate into 0.547 million metric tons of carbon.

Environmental Benefits

The previous calculations have demonstrated the amount of energy that is currently lost due to lack of durability in IG units. This energy loss situation will not improve unless measures are taken to provide the means and encouragement for the IG industry to improve their product durability. With no ratings standards to guide them and with no quantitative knowledge of the underlying failure mechanisms, some manufacturers in the IG industry will continue to make unreliable, performance-degrading product. The lack of product durability will translate directly to carbon dioxide pollution which impacts global warming. The purpose of this effort is to correct this unfortunate lack of durability situation.

The current IG product degradation results in significant loss of energy efficiency with respect to what could be achieved with a more robust product. This results in increased fossil fuel consumption and carbon dioxide generation that could be avoided.

An additional negative environmental effect results directly from the lack of product durability. This additional loss to the environment occurs due to the required replacement of performance degraded, non-durable IG product. When an IG unit fails and the consumer becomes dissatisfied with the loss of either optical properties or energy efficiency properties of the window, the consumer will tend to have the IG unit replaced. Although it is good from a window energy efficiency standpoint that a failed IG unit is replaced by a properly functioning one, there is a net energy loss to the environment due to the required energy draining production of the replacement unit. The embodied energy of the initial product is lost since it failed prematurely and required replacement. This loss of embodied energy is significant and is more significant the more rapidly the product fails.

Market Potential

If this lack of performance maintains at the current 10% rate, certainly this will have a negative affect on their perception of the product. As homeowners become aware of the unreliability of IG units it is quite possible they will be less likely to put them in their houses, either as initial windows or as replacement windows. The result will be a loss of energy savings as single lite units are used in the place of IG units.

Conversely, if IG units are made more durable, and the consumers' perception of the product improves, it is quite possible more homeowners will choose IG units, rather than single lite units for both new and replacement units. This pool of potential new users is immense, as approximately 75% of the market does not yet use IG units. With this large potential market coupled with the great increase in energy efficiency of the IG units compared to the single lite units, it is clear there will be significant energy savings resulting from penetration into this market. The potential benefit of penetrating this market will attempt to reach some state of quantification in the following.

By penetrating the current single glaze such that the total percentage of single glaze users reduces from 75% to 65%, the effective U-factor and solar heat gain for the average of this segment of the market will change as follows.

The new average U-factor across the previously non-IG market sector will become:

U-factor (new) = (0.87*1.25 + 0.13*0.27) = 1.123 Btu/hr ft^2 °F

The new average SHGC across the previously non-IG market sector will become:

SHGC (new) = (0.87*0.76 + 0.13*0.44) = 0.718

The improvement of U-factor for current non-IG consumers will be 10.2%. The improvement of solar gain of current non-IG consumers will be 5.5%.

The energy savings potentials are calculated in the following.
Current residential heating loads from residential windows

	Heating (Quads)	Cooling (Quads)
Conduction	1.45	0.01
Solar	-1.15	0.42
Total	0.3 Quads Heating	0.43 Quads Cooling

Assume:
The total % of consumers using non-IG units will decrease from 75% to 65%.

Conduction
10.2% heating energy savings from conduction * 1.45Q * .75 = 0.1109Q
10.2% cooling energy savings from conduction * 0.01Q* .75 = 0.0008Q

Solar Heat Gain
5.5% heating energy savings from solar heat gain * -1.15Q * .75 = -0.0474Q
5.5% cooling energy savings from solar heat gain * 0.42Q* .75 = 0.0173Q

Total Residential Current………………… 0.0816 Quads

Therefore, it is apparent that there is significant energy savings benefit, which can result by even slightly penetrating the current non-IG market sector with durable IG product. By reducing the market share of non-IG unit from 75% to 65%, the energy savings will be 0.0816 Quads. This potential savings is significant. Even if only a few percent of the market is penetrated the savings will be substantial. There is some market judgment necessary to determine to what extent the non-IG market will be penetrated by durable IG product. Common sense dictates, however, that there will be some penetration of this market as consumers appreciate the quality and energy benefits of increased durability products. The continuing negative perception of IG unit performance will of course be mitigated as the durability increases. With this effort, the tide of consumer perception will be turned to a more favorable result.

Many of the assumptions that have been used in the previous analysis have been used in similar energy calculations. There has been little or no conversation or questioning of these assumptions except the assumptions made around current IG failure rates. As presented, the basic assumption was that after 10 years in the field, 10% of the existing IG units will have failed and reference is given to the Results of SIGMA 10-Year Field Correlation Study. This study continues and results of IG failure remain similar.

In addition to the SIGMA data, the industry supply chain provided laboratory data to the project team (Appendix 4) generated as part of an IG certification screening process. The process was intended to evaluate a subset of IG units that were assembled as part of an industry certification procedure. The screening tests may have occurred before the remaining IG units in the set were submitted for certification, but the majority of units were received and tested after the certification process had been completed. Again, none of the screening units had been previously tested, installed or assembled in a sash frame. The total screening procedure is rigorous and time consuming involving a series of standardized test procedures and custom test procedures as described by the contributor and verified by the project team.

The first procedure was a simple procedure that was not intended to stress the unit but rather to check for any initial holes in the system. This first procedure was initiated in an effort to keep testing costs down. If the unit had a hole in the seal system immediately out of the box, it was rejected for further testing.

The results on several common IG designs showed an infant mortality (units that failed the initial leak test) rate of 6.7 % and an overall failure (units that passed the initial leak test and failed at some point in the remaining procedure) rate of 22%. Thus, the assumed failure rate of 10% in the first 10 years is not an unreasonably harsh assumption and, in fact, may be low as new data is made available and analyzed.

Returning to the proposal; the following Tasks were defined, and initiated;

2.2 Phase I

- List and Description of Tasks (Tasks 1, 2, 3 were delivered, end of Phase I, Appendix 1)

2.2.1 Task 1 – Review of Current Literature

The first task of this effort was an in-depth survey of existing literature. The literature reviewed included previous research regarding IG unit failure mechanisms, a survey of product design information, current testing protocols, and review of relevant reliability and durability literature.

2.2.2 Task 2 – Determine Current System Durability of Representative IG Products

A quantified definition of IG unit failure must first be determined. This definition will drive the meaning of the durability results derived. To ensure the results will receive broad acceptance in the IG industry, a team of industry experts was convened to develop a definition of failure. A Failure Mode and Effect Analysis (FMEA) was then performed for representative IG units to determine the relevant modes by which the defined failure can occur. The FMEA was defined a system diagram which represents the relationships of individual failure modes to overall IG unit performance. The durability of existing systems was then quantified by incorporating observed field failure statistical distributions of the individual failure modes into the system model.

2.2.3 Task 3 – Investigate and Quantify Failure Mechanisms

This task involved detailed evaluation of the failure modes identified in the FMEA. The failure modes were evaluated quantitatively towards the goal of developing mechanistic models. Analysis of the failure modes resulted in an improved understanding of the underlying failure mechanisms. The mechanistic models of the individual failure modes were evaluated either empirically or through direct mathematical development of physics-based failure model. The relationships of failure modes to the entire system as well and the interrelationships among the failure modes were evaluated and quantified. In evaluation of the failure modes consideration was made as to whether they are typically produced by faults in manufacturing methods or in design flaws. Evaluation of flaws in either of these regimes provided useful information for manufacturers of IG units. Task 3 was designed as a transition phase into Phase II and Task 4 of the project.

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(Note: The ASTM procedures were approved and printed after the completion of Phase I but before the completion of Phase II.)

3. Phase II Proposal and Approach Summary

Michael L. Doll

3.1 Task 4 – Develop Predictive Durability Design Tool

The mechanism-based IG unit durability was developed by incorporating the individual mechanistic failure mode models into an appropriate system model. The system model's relationship to the failure modes was the quantitative expression of the FMEA. The resulting quantitative mechanistic-based system model could then be used for prediction of product performance. The predicted output performance would include spacing and energy efficiency or other identified failure measure as a function of time. Using the definition of what level of product degradation constitutes failure, the system durability over time could then be determined. The model was then used for performing sensitivity studies with respect to system designs and their environment. Template charts were developed for use by designers in sizing, for example, IG systems for acceptable durability in their intended environment.

3.2 Task 5 – Develop Protocol for Accelerated Test Correlated to Service Life

The quantitative mechanistic failure mode and system models developed can be used for development of accelerated life tests which have a direct correlation to time durations of service exposure. The first portion of this effort requires theoretical methodology development. This involves developing a test from the defined mechanistic system and failure mode models. The test can be performed by either increasing the stress variables on the system, decreasing the strength of the system, or a combination of both in order to get a useful accelerated life test. Once the methodology is defined, the necessary test fixtures can be developed and implemented. The test could then be validated by correlating the results with the observed field data to ensure the expected correlation is obtained. This work remains to be done by the next generation of users.

3.3 Approach, Phase II

At the transition from the Phase I to Phase II, several activities outside the direct influence of the project team took place. These changes provided for both challenges and opportunities in meeting the project goals. In addition, the objectives (focused on validation of created models and envisioned test method developments) were heavily dependent on data representing the current field satiation. The very limited field data which has been available has been at such a low level of resolution that validation of root case failure modeling was unachievable. As a result, defining direction and prioritizing current and future test methods development was severely limited.

The overall team response to these challenges was based on building contingency plans around a clear vision that would still meet project goals and expectations. The originally defined tasks that were affected by these new constraints were Task 4 and 5; Task 5 to a much larger degree.

The new plans were implemented and included an opportunity to take the assembled systems model (described in Task 4) to a higher level of usability as a computer based IG durability simulation program. Focus and effort shifted toward completing this task as a major deliverable and major support for Task 5 as a prioritization tool.

Following previous successes in computer based simulation model development, the initial design had a main module to include IG durability code and graphical interface. The intent was to control input and output from modules that were either to be developed or currently in use as represented in Figure 3.1. Some of these modules were to be addressed as dynamically linked libraries (dlls) and contain the fundamental mathematical models; others contained the databases necessary to carry material properties, environmental data, etc.

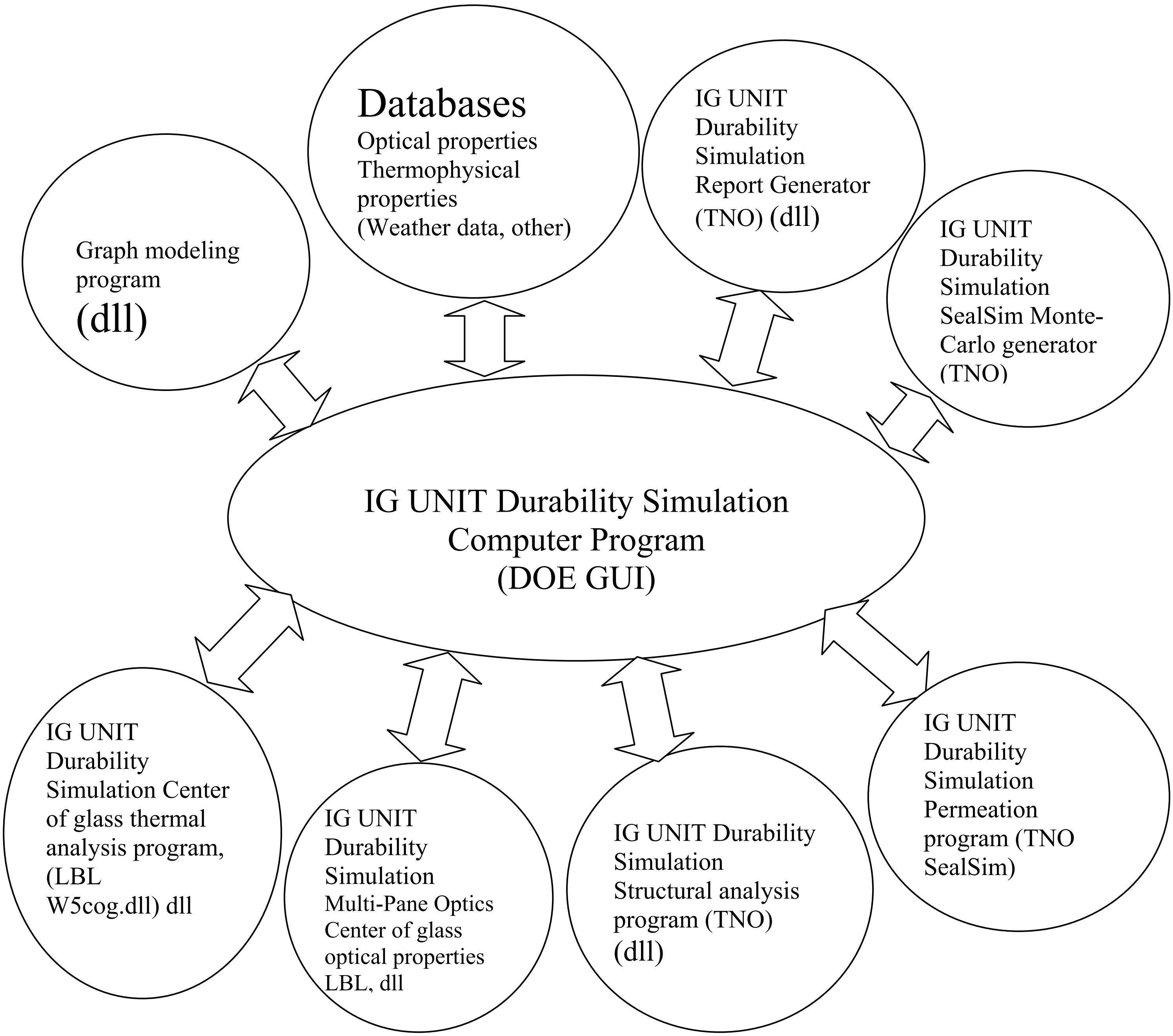


Figure 3.1 Initial Durability Program Design

Several months into the revised effort it become obvious that, in consideration of the project timeframe, budget, and unrealized complications embedded in the original FMEA analysis methodology, the team was overly optimistic in what could be accomplished and to what level of resolution. Focus and priority was given to the development of the physical models, database definition and development, model coupling, etc. building the foundation of the simulation program. The new focus produced the program flow of a time-step based simulation presented in Figure 1.6. The delivery of a workable durability model would set the stage for moving to full FEMA implementation in the future.

4. Development of a Predictive Durability Design Tool

Michael L. Doll, Dr. Russell Pylkki,
Gerry Hendrickson, Dr. Charlie C. Curcija
TNO Development Team

4.1 Scope and Goal

The following discusses the general scope of the first iteration of the insulating glass durability simulation program. This discussion begins with general statements of durability definition and application as applied to the development of the simulation tool as well as the project as a whole. The intent is to present the relationship, similarities and differences, between reliability and durability, focusing on the stress cycling which an IG experiences throughout its life, similar to the cycling of a mechanical device. The durability analysis can be applied in the same way.

The development of the simulation tool and an example of its use and application will be presented. This discussion will present opportunities and challenges in using and applying this first iteration design support tool and its value to the IG design process. The supporting databases will be discussed. The similarities and differences between the original FEMA methodology and this first iteration will be presented. Compatibility with current simulation tools and requirements for validation will be discussed. In addition, periodically, opportunities addressing IG component and assembly quality and process considerations will be presented.

4.2 Durability and Reliability

Durability is a term applied to devices that have a longer life than one-time use. Building materials, automobiles, and most tools are considered durable since their proper operation must continue over many uses and for a (long) period of time. At the other extreme, a paper plate and a hot dog are not considered durable since they are consumed during their first use. Being durable is typical of those items which have a high cost that must be amortized over many uses (or a long time period) to reduce the cost per use to an acceptable value.

Reliability is sometimes confused with durability. Reliability is the expectation that an item or object will work properly the next time it is used. For a one-time use item, such as ammunition and hot dogs, high reliability means that the user expects the item to function as expected when it is used. For an object such as an automobile, the user expects the item to work properly the next time it is used. For a window or other building component, the expectation is that the item will work properly during the entire time that the building exists. When a building component fails to be reliable, either that component or the entire building needs to be repaired or replaced.

Reliability may be expressed statistically by a number which represents the expectation that the units in a group have an expected successful operation rate for a specified period of time. When expressed as a reliability index, a value of 1.00 implies that no failures will be found in the group of objects exposed to some specified exposure conditions for a specified period of time or a specified number of operation cycles. A reliability index of 0.40 implies that 40% of the objects are expected to survive the specified exposure or number of cycles. When objects are subjected to varying conditions or to various types of loading, the reliability for each condition may be measured separately, and the combined reliability is found by computing the product of the reliability indexes from the individual reliability tests. For example, a relay may have a rating of 200,000 cycles at full rated load and a rating of 1,000,000 cycles at zero loads. For testing purposes a group of relays would be cycled at the rated load and a different group of relays cycled at no load. The overall reliability would be the product of the reliability index found for each group. When cycling a group of objects, some failures are considered random in nature where the occurrence of a failure can come at any point during the cycling, and other failures are considered wear-out failures when the expectation of failure increases with time or number of cycles of use. Statistically, these two types of failures have their reliability calculated with different statistical formulas and then the combined reliability is the product of the individual reliability values.

The generally accepted durability definition based on the mathematical models presented in Phase I of this project is not easily determined with the presently used testing methods described in U.S. and European test standards and in the IG certification tests. Further development and new test methods are required to properly assess the life of an IG when subjected to the loads and stresses found in typical building constructions and environmental exposures.

4.2.1 Durability as Applied to the Insulating Glass Unit

Durability, as applied to an IG unit, is the expectation that a certain percentage of IG units installed in typical building constructions will function as expected after a total installation time of some specified number of years. The window containing the IG unit (as well as the IG unit) has a cost higher than a consumable one-time use object would have. The cost of replacing an IG unit is also not trivial. The embedded cost in terms of energy and materials to manufacturer an IG unit must be amortized over the life of the unit. Typical manufacturers at the present time have warranties that vary from 5 years to 20 years, while the expected service life of the building is far longer.

Durability of an IG unit is affected by the applied loads and stresses from the environment as well as applied loads from the building structure and the building occupants. Normal environmental stresses are caused by wind loading, temperature and humidity changes, barometric pressure changes, and solar radiation. Environmental stresses are also related to the position of an IG unit in the building, such as south facing, north facing, elevation above ground, and reflectance of radiation and heat from surrounding walls and construction elements.

Building conditions that affect IG unit stresses may be caused by settlement of the building and by walls that shift due to sagging and warping as well as other conditions. Building occupants also have an effect on IG unit durability from operation of a window and various loads applied to the window and to the IG unit.

Some of the stresses applied to an IG unit are considered random, such as occupant loading of the glass and glass breakage. Other stresses are in the wear-out arena such as cyclical loading from temperature, humidity, barometric pressure changes, and occupant cycling. There are two major cycling events at work on building construction materials; daily changes in weather and seasonal changes in weather (climate).

Calculation of usable reliability indexes requires that the effect of each of these stresses be categorized into random or wear-out type so the statistical values can be correctly calculated.

Accelerated testing to determine reliability must recognize the type of failure. A further requirement of fully defining reliability from testing is that each of the perceived stresses be appropriately applied during testing of IG units. The present ASTM, SIGMA, and EN standard tests do not fully examine all of the conditions to which an IG unit is exposed. New tests will be required to enable the correct calculation of overall reliability.

Higher reliability will result in a more durable IG unit. The same IG unit design can also have reliability tested for, and calculated for, differing application conditions. When application conditions are more severe, reliability and durability will be lower. An individual IG unit design may have an adequate life and durability in certain types of construction in certain geographical areas and inadequate durability in other areas.

Stationary building materials are exposed to the same stresses and loading as IG units. Most stationary building materials are assembled into units with a high degree of stiffness. Materials such as brick and masonry have high intrinsic stiffness due to their high modulus. In window assemblies, only the diagonal direction is stiff due to the plate effect of the glass sheet. Windows are not stiff in bending and torsion.

Stresses that are applied to the IG in a building are caused by three main aspects. The first is the environmental conditions at the window location. Air temperature both inside and outside may cause the glass lites to deflect due to the change in internal pressure resulting from the interior gas reacting to the gas laws. Barometric pressure changes from weather patterns also cause changes in glass lite deflection, again due to the gas laws. Wind pressure and building envelope interior pressure causes the glass lites to bow outward or inward from applied air pressure differentials. Solar heat can warm the interior air space resulting in expansion of the internal gas and thus deflection of the glass lites. A further effect of interior and exterior temperature changes is the thermal expansion of the glass and spacer elements which results in shear forces on the sealant system. All of these stresses are cyclical in nature with hourly, daily, and seasonal weather changes. These stresses may cause a build-up of response in the IG materials and will induce wear-out failures.

The elevation of the IG installation in relationship to the elevation when the IG was sealed may result in a permanent stress that is then added to the other stresses that the IG is exposed to. Building an IG unit or final sealing of the IG cavity, at the same average conditions as the installation condition will reduce this initial stress offset in the IG.

4.2.2 Insulating Glass Stress Cycling

Cycling of basic building materials, other than IG units, from environmental conditions such as weather is normally limited to thermal and moisture expansion and contraction. Basic building materials do not contain sealed volumes that are subject to stress from expansion of trapped gases. Materials such as masonry and other inorganic materials have proven, long-term life expectancy when properly designed and installed. Materials such as wood and other organic materials must be protected from moisture that can adversely affect the long-term life. Moisture absorption by wood and some organic materials may promote mold growth. Durability of materials other than IG units varies widely and is dependent on proper installation and maintenance. The range of built structures has a proven record of acceptable durability when properly maintained and thus is the standard that IG units are compared to. Presently, IG units do not have as long a predicted service life as the structures they are installed in.

4.3 Development of the Computer Based Durability Simulation Tool

Environmental stressors acting on the IG unit include temperature, pressure (barometric and wind), solar radiation, and differing rates of thermal expansion (Figure 4.3.1). As a function of time, the durability design tool simulates the behavior of an IG unit exposed to realistic climate conditions. As the environment acts upon the IG unit, stresses and strains in the IG unit are calculated together with temperature distributions, gas permeation effects (gas loss, desiccant moisture loading), dew point temperature in the IG unit air space, and changes in the heat transfer through the IG unit. The effects of the environmental exposure on the IG unit are compared against the strength of the window assembly to determine the durability of the design.

In order to carry out the simulation, the IG unit's response to environmental stressors is separated into three different models:

Thermal Model
Permeation Model
Stress Model

The following sections will describe in detail the development of the sub-models and the manner in which they are coupled.

Of the five IG unit design classes described in the Phase I Report, two were developed into the simulation:

Box Spacer System
Thermoplastic Spacer System

These were chosen because they represent fundamentally different designs and would require the development of a more sophisticated permeation model that could deal with the diffusion of gases and moisture through a seal as they are simultaneously adsorbed by the desiccant in the sealant.

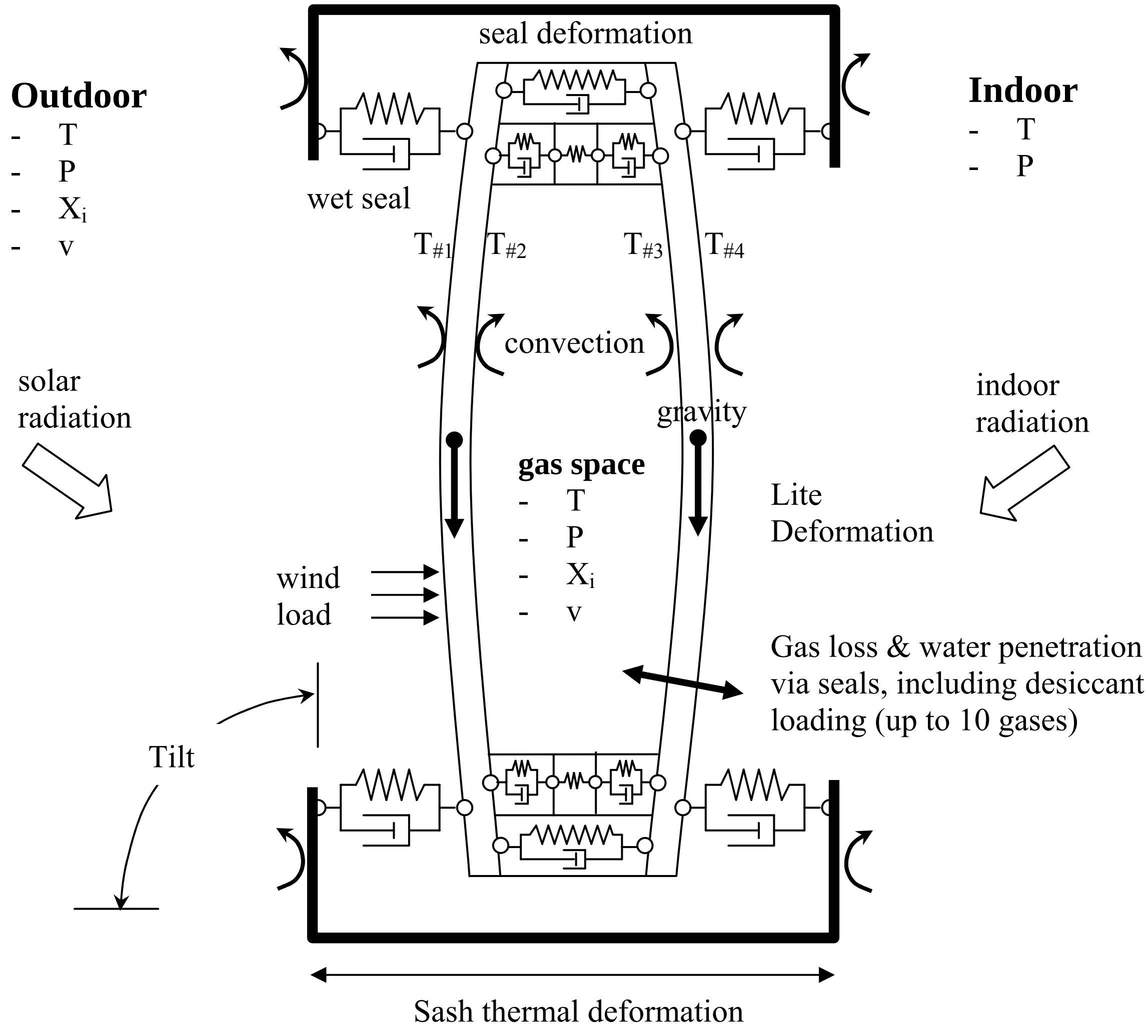


Figure 4.3.1 Impression of the representation in SealSim of an IG 7unit (Box Spacer) and indication of the physical effects modeled (T is temperature, P is pressure, X_i is composition, v is velocity)

4.3.1 Design and Development of the Sub Models

The simulation contains three models; the thermal calculations, the permeation of gases (including water) through the sealants and the structural model to determine the stresses and strains on the system. These models are presented below. Additionally the models are coupled in an iterative fashion, such that the calculations for properties at each time increment converges before the next time step is taken and new climate data is input into the model.

Thermal Model

In the thermal model, for each time step:

- The sun incident angle on the IG unit is determined
- The long wave optical properties of the individual coated or uncoated lites of the double glazing unit are extrapolated from values available at normal incidence from the glazing database.
- The long wave optical properties of the double glazing unit are calculated at the sun incident angle.
- A "center of glass" calculation is performed; conforming to (ISO 15099), where the gap width of the IG unit is taken equal to the average gap width at that moment, given the temperatures of the gas space and the glass lite surfaces. For the current gas composition, the composition at the specific time step is used. Note that non-standard climate data is used to calculate the temperatures and U-factor, based on climate conditions varying in time as selected by the user.

- The one-dimensional temperature distribution in the sash is calculated, in a way similar to the procedures ISO 15099, where the frontal surface area of the frame is taken as the effective surface area for heat transfer.

- Note: Heat transfer to other elements of the system via the wet seal is not modeled.

For a box-spacer:

- The spacer bar temperature is taken equal to the gas space temperature

- The seal temperature towards the indoors is taken equal to the average of the gas space temperature and indoor glass lite surface temperature (surface #3).

- The seal temperature towards the outdoors is taken equal to the average of the gas space temperature and outdoor glass lite surface temperature (surface #2)

- For a TPS spacer, the seal temperature is taken equal to the average outdoor glass lite temperature (surface #2) and the indoor glass lite surface temperature (surface #3).

    - Note: The seal and spacer temperatures are set equal to the average of the adjacent lite and gas-fill temperatures. Heat balance is performed to determine lite and gas-fill temperatures and seal temperatures are set equal to average values among these as described above.

- The wet seal towards the outdoors is taken equal to the outdoor glass lite temperature (surface #1) and the wet seal towards the indoors is taken equal to the indoor glass lite temperature (surface #4).

Procedure for Calculating Sun Incident Angle on IG Unit

The incident angle of sun radiation on the window as a function of time and IG unit location is calculated according to the procedure described in the ASHRAE Fundamentals Handbook 2001, SI Edition, and Chapter 30. Normal incidence corresponds to 0°. The IG unit does not receive any direct sun radiation when the incident angle is outside the range –90° to 90° or when the sky is completely covered.

The total solar radiation incident on an inclined surface is the sum of the direct beam radiation, the sky diffuse solar radiation (e.g. reflected from clouds, and scattered radiation) and the ground-reflected radiation, also assumed to be diffuse. Note: Only the direct beam contribution to total solar radiation is calculated in this initial simulation. All calculations involving solar radiation are based on solar time.

<u>Solar Time</u> is based on the apparent angular motion of the sun across the sky with solar noon defined as the time that the sun crosses the meridian of the observer. Local standard time (LST) is converted to solar time by first correcting for the difference in longitude between the location and the meridian on which the local time is based (Eastern, 75 Deg W; Central 90 Deg W; Mountain 105 Deg W; Pacific 120 Deg W; Hawaii-Alaska 150 Deg W). Note that one degree in longitude is equivalent to 4 minutes in time (since 360 degrees is one day). An additional correction is the equation of time (ET), which takes into account changes in the earth's velocity as it orbits the sun. Due to the cyclic change in orbital velocity as the earth passes from its closest approach to the sun (aphelion) to its furthest separation (perihelion), there is a cyclic difference between the apparent solar time, as indicated by a sundial, and the time indicated by a clock, which runs at a uniform rate:

The apparent solar time (AST), calculated from the local standard time, is given by

$$AST = LST + ET + 4\,(LSM - LON)$$

Where

AST = apparent solar time, minutes

LST = local standard time

LSM = local standard time meridian, degrees

LON = local longitude, degree

4 = minutes of time required for a 1 degree rotation of the earth

ET = equation of time, minutes

$$ET(n) = \left(9.87 \sin\left(4\pi \frac{n-81}{364} \right) - 7.73 \cos\left(2\pi \frac{n-81}{364} \right) + 1.5 \sin\left(2\pi \frac{n-81}{364} \right) \right) * \text{min}$$

Where n = day of year (1 - 365)

Solar Geometry: The position of the sun and the geometric relationships between a plane and the direct beam solar radiation incident upon it (see
Figure) may be described in terms of the following angles:

L, latitude, is equal to the angle of the location relative to the equator; North is positive.

δ, declination, is equal to the angular position of the sun at solar noon with respect to the equatorial plane (varies from -23.45 to 23.45 degrees).

α, solar altitude, is equal to the angle between the sun's rays and the horizontal (between 0 and 90 degrees).

z, zenith angle, is equal to the angle between the sun's rays and the vertical.

ϕ, solar azimuth, is equal to the angle between the horizontal projection of the sun's rays from due south (positive in the afternoon).

γ, surface solar azimuth, is equal to the angle between the projections of the sun's rays and of the normal to the surface on the horizontal plane.

ψ, surface azimuth, is equal to the angle between the projection of the normal to the surface on a horizontal plane and due south (east is negative).

β, tilt (slope), is equal to the angle between the surface and the horizontal (0 - 180 degrees).

Θ, the angle of incidence, is the angle between the solar rays and a line normal to the surface.

The position of the sun may be expressed as a function of solar altitude and the solar azimuth as shown in

Figure 4.3.2 below. These angles are a function of the local latitude L and the solar declination δ, which is a function of the date and the apparent solar time (AST) expressed as the hour angle h:

h = 0.25 (number of minutes from local solar noon) given in degrees.

(Note: h is positive in the afternoon.)

The declination angle is given by:

$$\delta = 23.45 * \deg * \sin\left(360 * \frac{284+n}{365} * \deg\right)$$

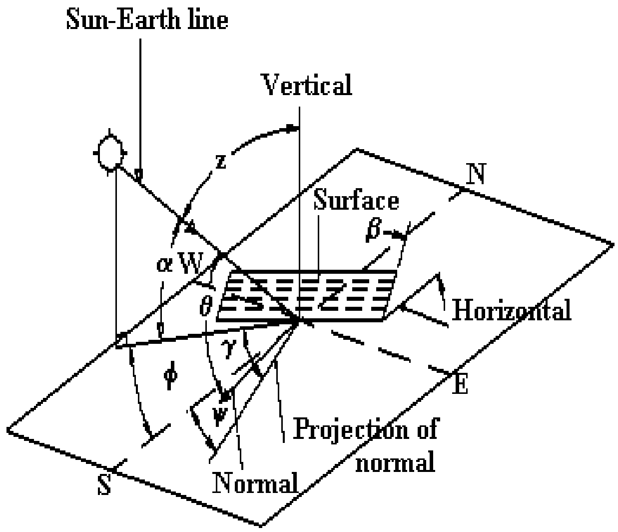


Figure 4.3.2 Definition of Solar Position

z = Zenith angle

θ = Incident angle

α = Solar altitude

φ = Solar azimuth

β = Tilt angle

ψ = Surface azimuth angle

γ = Surface solar azimuth

$$\alpha = \arcsin(\cos(L)\cos(\delta)\cos(h) + \sin(L)\sin(\delta))$$

$$\phi = \arccos\left(\frac{\sin(\alpha)\sin(L) - \sin(\delta)}{\cos(\alpha)\cos(L)}\right)\frac{h}{|h|}$$

As can be seen from the diagram:

$$z = 90° - \alpha$$

$$\gamma = \phi - \psi$$

(Note that ψ is negative and ϕ positive in the sketch)

$$\theta = \arccos\left(\cos(\alpha)\cos(|\gamma|)\sin(\beta) + \sin(\alpha)\cos(\beta)\right)$$

angle of incidence (if γ is greater than 90° or less than 270°, then $\gamma=0$)

Angular Dependence of Glazing Optical Properties

The angular dependence of a single lite of coated or uncoated glass is extrapolated from its normal properties by the procedure described in ASHRAE Fundamentals Handbook 2001, SI Edition, Chapter 30: “Determining the properties of uncoated glazing layers from normal incidence measurements”. This extrapolation uses angular data for CLEAR and BRONZE glass as found in ASHRAE 30.22, Table 12.

Optical Properties of the Double-Layer Glazing System

For the determination of the optical properties of a double-glazing system, follow the procedure described in ASHRAE Fundamentals Handbook 2001, SI Edition, Chapter 30 “Optical Properties of Multi-Layer Glazing Systems”.

Permeation Model

The permeation model calculates the movement of gases (including water) with time though the IG unit polymer sealants. Though the movement of an individual gas molecule at a given moment is completely random, in general, a net flow of a gas through the sealants occurs when the concentrations of the gas on either side of the seal are not equal. For the TPS system, the inner sealant is formulated with a desiccant to adsorb the water vapor as it diffuses into the IG unit. The simulation takes into account the presence of the desiccant while calculating permeation. The permeation model is also used to calculate the moisture and gas loading of the desiccant present in the box spacer system. A detailed description of the permeation model is given below.

Diffusion Equation for Multiple Gases in a Polymer Matrix Mixed with Desiccant

The diffusion of gases through polymer material is assumed to be governed by the absorption-desorption mechanism shown below in Figure In the first step, the gas is adsorbed onto and dissolves into the polymer sealant. In the second step of the permeation process, the dissolved gas diffuses through the sealant. In the final step, the gas comes out of the polymer and desorbs from the surface.

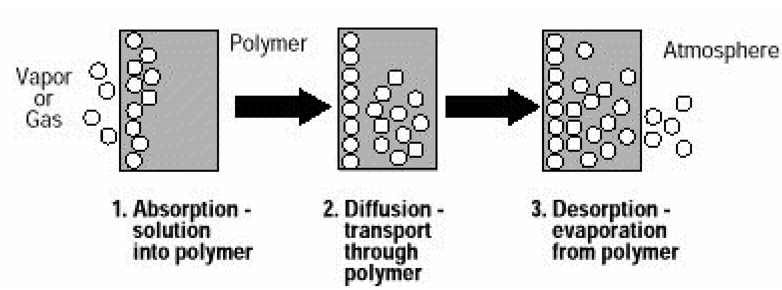


Figure 4.3.3 Permeation of Gas through Polymer via Absorption-Desorption Mechanism

The general equation for one-dimensional spatial, time dependent gas diffusion through a polymer slab, mixed with desiccant is given by:

$$v_p \frac{d\,c_{p,i}}{dt} + (1 - v_p) \cdot \frac{d\,c_{d,i}}{dt} = \frac{v_p}{\tau} \cdot \frac{d}{dx}\left(D \cdot \frac{dc_{p,i}}{dx} \right)$$

Desiccant is assumed to be an immobilizing agent for permeation. If no desiccant is present, the diffusion equation simplifies to:

$$\frac{d\,c_{p,i}}{dt} = \frac{1}{\tau} \cdot \frac{d}{dx}\left(D \cdot \frac{dc_{p,i}}{dx} \right)$$

Where ‘t’ denotes time, and ‘x’ the distance through the seal in direction of diffusion, the index ‘i’ denotes the specific gas involved. When ‘n’ gases are involved, ‘n’ similar differential equations have to be solved. The volume fraction of polymer in a mixture of polymer and desiccant is defined as:

$$v_p\,[m^3 \text{ polymer}/m^3 \text{ mixture}]$$

The polymer - desiccant mixture is assumed to be homogeneously mixed. The desiccant fraction is given by:

$$v_d = (1 - v_p)$$

The concentration of gas ‘i’ dissolved in the polymer material is assumed to be proportional to the (partial) gas pressure ‘p_i’ of gas ‘i’ [Pa] according to Henry’s law:

$$c_{p,i} = S_i \cdot p_i \quad [kg\ gas_i/m^3\ polymer]$$

Where ‘S_i’ is the solubility of gas ‘i’ in the polymer material according to:

$$S_i \quad [kg\ gas_i/m^3\ polymer/Pa]$$

The permeation coefficient ‘P_i’ of gas ‘i’ in the polymer is defined by:

$$P_i = D_i \cdot S_i \ \left[\frac{m^2}{s} \frac{kg\ gas_i}{m^3\ polymer} \cdot \frac{1}{Pa} \right]$$

Where ‘D_i’ is the diffusion coefficient of gas ‘i’ in the polymer

D_i $[m^2/s]$

For simplicity it is assumed that the solubility, diffusion coefficients and permeation constants of the gases are independent of each other. The concentration of gas absorbed by the desiccant is given by a Langmuir sorption isotherm, in the case of a single gas:

$$c_d = c_{\max} \frac{b \cdot p}{1 + b \cdot p} \quad [kg\ gas_i/m^3\ desiccant]$$

The factor 'b' [1/Pa] determines the shape of the Langmuir sorption isotherm. Note that if 'b' is small the concentration becomes proportional to pressure. In this case the concentration is given in somewhat different units:

$$c'_d = \quad [kg\ gas_i/kg\ desiccant]$$

The definitions of the concentrations can be expressed as follows:

$$c_d = \rho_d \cdot c'_d$$

Where the desiccant density is given by:

$$\rho_d = \quad [kg\ desiccant\ /\ m^3\ desiccant]$$

The absorption of multiple gases by the desiccant is assumed to be governed by the (LRC) Loading Ratio Correlation, an extension of the Langmuir isotherm for a single gas according to:

$$c_{a,i} = c_{\max,i} \frac{b_i \cdot p_i}{1 + \sum_{all\ gases} b_i \cdot p_i} \quad [kg\ gas_i/m^3\ desiccant]$$

Solubility, diffusivity and Langmuir shape factor are assumed to be exponential functions of temperature [K] according to:

$$S = S_0 \cdot e^{S_c/T}$$
$$D = D_0 \cdot e^{D_c/T}$$
$$b = b_0 \cdot e^{b_c/T}$$

From the definition of permeability, it follows that the permeability is also an exponential function of temperature:

$$P = P_0 \cdot e^{P_c/T} \quad where \quad P_0 = D_0 \cdot S_0 \quad and \quad P_C = D_c + S_c$$

The desiccant in the polymer matrix acts in general as an immobilizing agent, increasing the distance over which diffusion takes place in the polymer. This increase in length is assumed to be a linear function of the amount of desiccants in the polymer matrix, according to:

$$\tau = 1 + \tau_0 \cdot v_d \quad [m/m]$$

Resulting diffusion equation in terms of pressure

Inserting the definitions in the diffusion equation, gives a diffusion equation in terms of partial pressure. For gas 'i' the expression reads:

$$v_p \frac{d\, S_i \cdot p_i}{dt} + (1 - v_p) \cdot \frac{d\left(c_{\max,i} \dfrac{b_i \cdot p_i}{1 + \sum_{all\ gases} b_i \cdot p_i} \right)}{dt} = \frac{v_p}{1 + \tau_0 \cdot (1 - v_d)} \cdot \frac{d}{dx}\left(D \cdot \frac{dS_i \cdot p_i}{dx} \right)$$

Where:

$$S_i = S_{0,i} \cdot e^{S_{c,i}/T}$$
$$D_i = D_{0,i} \cdot e^{D_{c,i}/T}$$
$$b_i = b_{0,i} \cdot e^{b_{c,i}/T}$$
$$P_i = P_{0,i} \cdot e^{P_{c,i}/T} \quad where \;\; P_{0,i} = D_{0,i} \cdot S_{0,i} \quad and \quad P_{C,i} = D_{c,i} + S_{c,i}$$

So when, for example, '10' gases are involved in permeation, '10' similar differential equations have to be solved in terms of partial pressures of the gases. A complicating factor that the equations are interdependent (coupled) via the summation term over all gases in the expression for the LRC Langmuir sorption isotherm.

Initial Conditions and Boundary Conditions

When solving the differential equations, the partial pressures of the gases, on either side of the polymer slab, are assumed to be given. These boundary conditions may vary in time. The initial partial pressures at time zero (simulation start) of gases dissolved in the polymer and absorbed by the desiccant, are assumed to be given by the user. Either the partial gas pressures have to be entered or the total gas pressure in combination with the gas composition has to be entered by the user.

Numerics

The equations are discretised spatially using a finite volume formulation in conserved form. The equations are discretised backward in time, avoiding restrictions for the numerical time step in order to enhance numerical stability. The discretised coupled equations are solved by a gauss iteration process.

Example discretisation of the diffusion equation

Now we replace the diffusion equation, for simplicity we use the equation for a single gas:

$$v_p \frac{d\,c_d}{dt} + (1 - v_p) \cdot \frac{d\,c_a}{dt} = \frac{v_p}{\tau} \cdot \frac{d}{dx}\left(D \cdot \frac{dc_a}{dx} \right)$$

by its discretised counterpart, We take for example a small section ‘Δx’ of the polymer slab, having dimensions ‘Δy’ and ‘Δz’ in the other dimension directions, according to Figure 4.3.4.

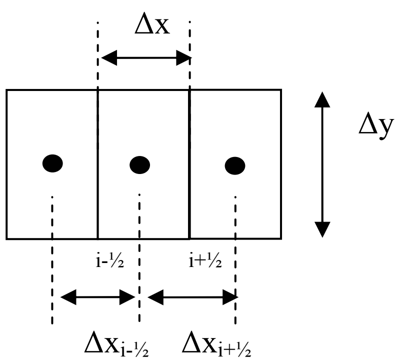


Figure 4.3.4 Discretisation of the Diffusion Equation, Control Volume with Nodes

The index ‘i’ now refers to the location of the grid node or interface position between control volumes. The index ‘0’ denotes a value the previous time t_0, the index ‘1’ denotes a variable at the current time t_1. The discrete time step is denoted by ‘Δt’. Filling in the discretisation gives:

$$\left[v_p \frac{c_{p,i}^1 - c_{p,i}^0}{\Delta t} + \left(1 - v_p\right) \cdot \frac{c_{d,i}^1 - c_{dp,i}^0}{\Delta t} \right] \cdot \Delta y \cdot \Delta y \cdot \Delta z = \frac{v_p}{\tau} \cdot \left(D_{i-1/2} \cdot \frac{c_{p,i-1}^1 - c_{p,i}^1}{\Delta x_{i-1/2}} - D_{i+1/2} \cdot \frac{c_{p,i+1}^1 - c_{p,i}^1}{\Delta x_{i+1/2}} \right) \cdot \Delta y \cdot \Delta z$$

So for every grid node ‘i’, a discretised equation is obtained. The permeation flux over a volume interface ‘i-½’ is given by:

$$\phi_{i-\frac{1}{2}} = \frac{v_p}{\tau} \cdot \left(D_{i-\frac{1}{2}} \cdot \frac{c_{p,i}^1 - c_{p,i-1}^1}{\Delta x_{i-\frac{1}{2}}} \right) \cdot \Delta y \cdot \Delta z \quad [kg\ gas / s]$$

Conversion expressions from volume fractions to mass fractions and vice versa:

Assume we have mass polymer M_p [kg] and volume polymer V_p [m3].

Assume we have mass desiccant M_d [kg] and volume desiccant V_d [m3].

The density of the polymer and of the desiccant is:

$$\rho_p = \frac{M_p}{V_p}$$

$$\rho_d = \frac{M_d}{V_d}$$

Now we mix the polymer and desiccant. The mass fraction and volume fraction polymer is:

$$m_p = \frac{M_p}{M_p + M_d} = \frac{\rho_p \cdot v_p}{\rho_p \cdot v_p + \rho_d \cdot (1 - v_p)}$$

$$v_p = \frac{V_p}{V_p + V_d} = \frac{\frac{m_p}{\rho_p}}{\frac{m_p}{\rho_p} + \frac{1 - m_p}{\rho_d}}$$

Diffusions in Zeolite Beads (Box-Spacer)

Zeolite is present in pellets (beads) in the gas space (spacer bar). Zeolite does have micro pores (typical size of Zeolite cages is in the order of a molecule diameter that is a few Å). It is assumed that the pellets do have (macroscopic) tortuous pores, with a typical pore diameter of 1 μ. In general, the mass transport of gases in the pellets occurs by two mechanisms (1) ordinary diffusion and (2) Knudsen diffusion. Ordinary diffusion, as described by Fick's law, dominates when the pores are large and the gas relatively dense. However, when the pores are small and/or the gas density low, the molecules collide with the pore walls more frequently than with each other, and diffusion of molecules along the pore wall is described by the equations of free molecules or Knudsen flow. We assume that predominantly Knudsen diffusion takes place. The effective diffusion coefficient thus is written as:

$$D_{eff} = \frac{\Psi}{\tau} D_{Kn}$$

Where Ψ is the porosity or volume void fraction of the pellet and τ the tortuosity factor that accounts for the increased diffusion length due to the tortuous path of real pores and for the effect of constrictions and dead pores. The Knudsen diffusion coefficient for species 'i' is given by

$$D_{Kn} = \frac{1}{3} d_{eff} c_{av}$$

Where d_{eff} is the effective pore diameter; the factor c_{av} is the average molecular speed of species 'i'

$$c_{av} = \sqrt{\frac{8\Re T}{\pi M_i}}$$

Where '$\Re$' is the universal gas constant, 'T' absolute temperature in Kelvin, and 'Mi' is the molecular weight of species 'i'. We assume that mass transfer in the pellet is the limiting factor. The mass balance for a bead can be shown, using a lumped approach, neglecting accumulation effects in the void relative to Zeolite adsorption:

$$\rho_d \cdot V \cdot \frac{d(c_{a,i})}{dt} = A_{eff} \cdot D_{eff} \cdot \frac{M_i}{\Re T} \cdot \frac{\left(p_{i,gas\,space} - p_i\right)}{\frac{d_{bead}}{2}}$$ [kg species i/s]

Where ‘V’ is the bead volume (assumed to be spherical), ρ_d is the desiccant bead density, and A_{eff} is the effective area for diffusion (the average bead surface area is taken $4/3\pi r^2$). The characteristic diffusion length has been taken as half the bead diameter d_{bead}. The right hand side of this expression denotes the flux of species ‘i’ form from the gas space to the desiccant. Desiccant absorption is again described by the Langmuir Loading Ratio Correlation sorption isotherm for multiple species (Einstein notation), described before:

$$c_{a,i} = \frac{c_{i,\max} \cdot b_i}{1 + \sum_{all\ gases} b_i \cdot p_i}$$

Note**: Entering tortuosity in SealSim 1.0**

In SealSim 1.0 the tortuosity factor τ cannot be entered, however this can be compensated for by entering for the porosity Ψ of the pellet not the actual value for the porosity, but the porosity divided by the tortuosity.

Expression for gas space pressure (mass balance gas space)

The gas space is assumed to be well mixed, and of homogeneous composition, which may vary in time. A mass balance of the gas space now is depicted as, for gas ‘i’:

$$\frac{d(\rho_{g,i} \cdot V)}{dt} = \phi_i \ \ [kg\ gas\ 'i'/s]$$

Where a positive value for ‘Φ_i’, denotes the net flux of gas ‘i’ moving towards the gas space, from the seals and/or desiccant beads in the spacer. So if ’10’ gases are present ‘10’ mass balance equations apply. We assume that the partial density of gas ‘i’ is given by the ideal gas law:

$$\rho_{g,i} = \frac{p_i \cdot M_i}{R \cdot T}$$

The expression for the mass balance now can be written as:

$$\frac{d\left(\frac{p_i \cdot M_i}{R \cdot T} \cdot V\right)}{dt} = \phi_i \ [kg\ gas\ 'i' / s]$$

The gas space volume and temperature can be functions of time, as well as the flux of gas 'i'. Backwards discretising in time gives:

$$\frac{\left(\frac{p_i^1 \cdot M_i}{R \cdot T^1} \cdot V^1 - \frac{p_i^0 \cdot M_i}{R \cdot T^0} \cdot V^0\right)}{\Delta t} = \phi_i^1$$

Where the index '0' denotes a value at the previous time t_0, the index '1' denotes a variable at the current time t_1. The discrete time step is denoted by 'Δt'. The gas flux towards the gas space is considered to be given by the permeation model, the temperatures at the current and previous time step by the thermal model, and the gas space volume at the current and previous time step by the structural model. The mass balance now results in an expression for the evolvement of the gas space pressure in time.

The total pressure in the gas space at any time is given by the sum of the partial gas pressures:

$$p_{tot} = \sum_{all\ gases} p_i$$

The gas composition of the gas space in terms of mole fractions (equivalent to volume fraction) is given by:

$$c_i = \frac{p_i}{\sum_{all\ gases} p_i} = \frac{p_i}{p_{tot}}$$

The average molecular weight of gases in the gas space is given by:

$$M = \frac{\sum_{all\ gases} p_i \cdot M_i}{\sum_{all\ gases} p_i}$$

The initial partial pressures of gases at time zero (simulation start) in the gas space, are assumed to be given by the user. Either the partial gas pressures have to be entered or the total gas pressure in combination with the gas composition has to be entered by the user.

Stress Model

The stress model calculates the physical stresses that act upon the IG unit with time. These stresses include the movement of IG unit components relative to each other that can take place due to the effects of thermal expansion or contraction, bending of the glass lites due to differences in pressure between the atmosphere and the IG unit gas space and wind loads. A detailed description of the stress model is given below.

Introduction

In the structural model for each time step:

The glass lite deformation is determined

The deformation of the inner, outer and wet seals is determined, where thermal deformation of the sash and spacer bar is taken into account. The seals behave visco- elastically (time-history effect).

Loads on the system (of glass lites and seals) taking into account the deformation calculations are:

- Pressure differences over the gas space,
- Wind loads (See ASHRAE Fundamentals Handbook 2001, Chapter 16) (see earlier note on wind load standards)
- Thermal expansion/contraction of the spacer bar
- Thermal expansion/contraction of the sash
- Thermal expansion/contraction of the glass lite
- Gravity

The structural response of an IG unit is assumed to be the (coupled) response of the insulating gas, the two glass lites, the seals and (if present) the metal spacer, to external loads and material degradation. The external loading is due to barometric changes, temperature and wind loads as examples, whereas material degradation includes degradation due to aging, chemical degradation and temperature changes. Hence, the structural response of the unit is dependent on the thermal behavior and on the composition of the insulating gas. Therefore, the model for the structural response of the IG unit is coupled with the thermal model for the unit and with the model for the gas permeation of the unit. These latter two models are described above and are not considered in this section. However, the chain of calculations to solve for the coupled models for structural response, thermal response and gas permeation will be discussed. To increase the computation speed, some mass balance calculations for the gas composition are considered in the model of the structural response as is explained below.

In the next section the chain of model calculations for a time step is described, followed by a discussion of the way the response of the two glass lites is determined. The coupling of this response with a lumped mass balance equation for the filling gas is then explained. The last section discusses how the response of the seals (and the metal spacer) is determined using a set of springs and dashpots.

Coupled Model Calculations

The coupling of the structural model with the thermal model and the model for the penetration of water vapor in the overall program is reflected in the calculation sequence depicted in Figure 4.3.4.

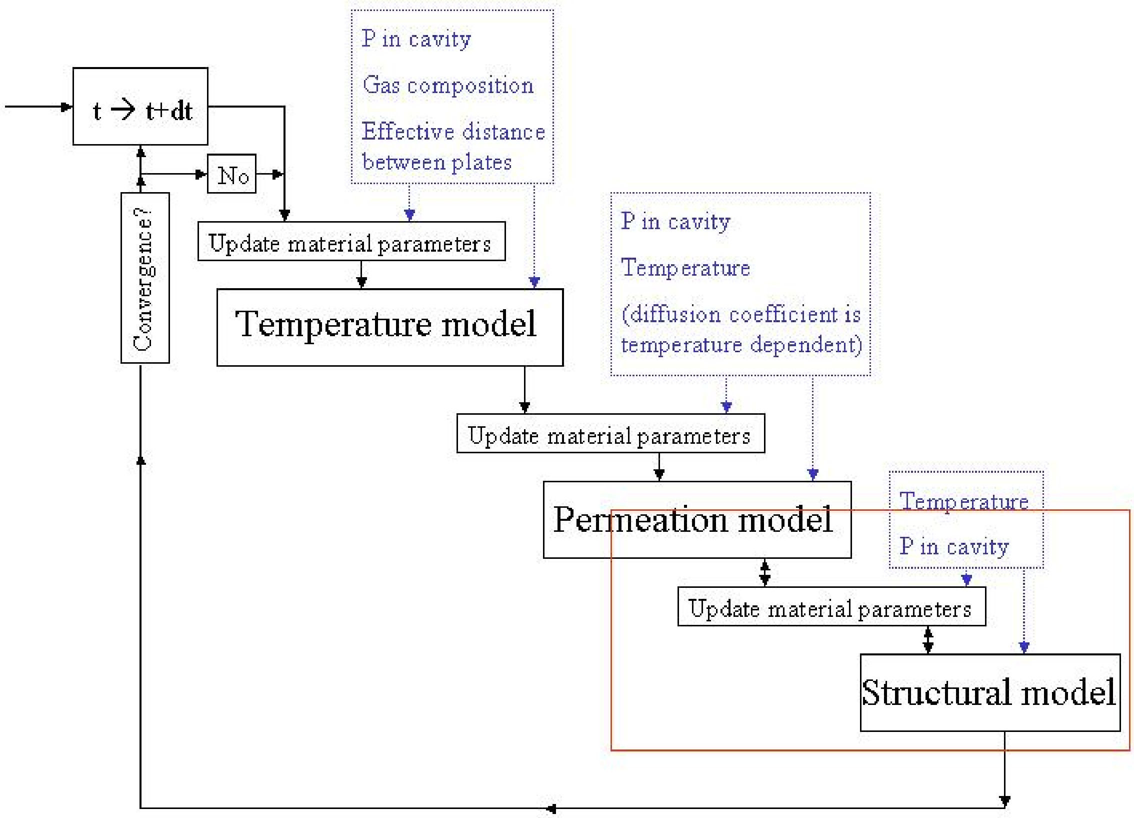


Figure 4.3.4 SealSim coupled model calculations

After each time increment (with time step, dt, box in the left-up corner), first the temperature model is solved, which is based on the most recently determined solutions for the permeation and structural models. In figure 4.3.4, the second model considered is the one for water vapor permeation, in which the most recently determined temperature and structural data is used. The last model is for structural response, where the most recent solutions for the temperature and the permeation models are used. This is reflected in Figure 4.3.4 by the blue boxes and connection arrows with both the model boxes and the boxes that indicate the actions to update the relevant material parameters.

As one such sequence of calculations may still result in solutions for the three (coupled) models that do not reflect a good balance, the solution procedure for the structural model is followed by a (convergence) check for balance. If one has obtained balance, the calculation procedure for this time step is terminated and the program proceeds with the next time step. When the balance is still not sufficient another sequence of model calculations is performed. This convergence check is based on the residuals for the model equations based on the most recently determined set of model solutions. These residuals have physical significance: For the temperature model this residual indicates a balance in heat exchange and for the permeation model it concerns a (molecular) mass balance.

For the structural model, two residuals are required for a convergence check, where one also equates to a check for mass balance. This is due to the fact that in the structural model there is already provision for a part of the coupling with the permeation model as is reflected in Figure 4.3.4 by means of the red box that covers the structural model and part of the permeation model. In the next section the bending of the glass lites is described, which will enable us to elaborate on this coupling. The other convergence check for the structural model concerns a balance of forces per unit length as will be pointed out later in this document.

Deformation of Lites under Loading

For the deformation of the two glass lites of the IG unit, it is assumed that such lites have a small length in the direction perpendicular to the lites (i.e. the thickness) in comparison with the two (horizontal and vertical) dimensions along the plate. Furthermore, it is assumed that the loads are such that the lite deflections in the perpendicular direction are much larger than the ones in the planes of the lites. Hence, only deflections in the perpendicular direction are taken into account, where it is assumed that these deflections are relatively small such that the classical elastic plate theory as described in Theory of Plates and Shells, Timoshenko and Woinowsky-Krieger (1959) may be assumed.

It should be noted that alternative models are available for deformation calculations for the two glass lites (e.g. Reissner, Kirchhof and Von Karmann non-linear plate equation). However, the current modeling approach does allow for fast (and relatively accurate) calculations. This aspect is quite important as the deformation model has to be applied many times during simulation runs with SealSim.

Let us consider now one lite with:

- a Horizontal length [m] of the lite
- b Vertical length [m] of the lite
- h Half the thickness [m] of the lite
- x Horizontal coordinate [m] with $0 < x < a$
- y Vertical coordinate [m] with $-b/2 < y < b/2$
- E Young's modulus [Pa]
- ν Poisson's ratio [-]
- q (Constant) load [Pa] applied in thickness direction

If one assumes the lite is simply supported, chapter 30 of Timoshenko and Woinowsky-Krieger (1959) gives us the following solution for w [m], the deviation in perpendicular direction,

$$w(x,y) = \frac{q}{24D}(x^4 - 2ax^3 + a^3x) + \frac{qa^4}{D}\sum_m^{\infty}\left(c_1 \cosh\left(\frac{m\pi y}{a}\right) + c_2\left(\frac{m\pi y}{a}\right)\sinh\left(\frac{m\pi y}{a}\right)\right)\sin\left(\frac{m\pi x}{a}\right)$$

Where in the summation m is only taken to be odd and,

$$D = \frac{2Eh}{3(1-\nu^2)}$$

$$c_1 = -2\frac{a_m \tanh(a_m) + 2}{\pi^5 m^5 \cosh(a_m)}$$

$$c_2 = \frac{2}{\pi^5 m^5 \cosh(a_m)}$$

And,

$$a_m = \frac{m\pi b}{2a}.$$

In order to determine the lite deflections accurately in the structural model, the summation is limited to a finite number of terms in such a way that the remaining (infinite number of) terms that are left out are (relatively) small.

In a similar way derived data can be determined out of the expression for the deviation w, such as:

M_{xx} Momentum per unit length [N]

M_{xy} Momentum per unit length [N]

M_{yy} Momentum per unit length [N]

Q_x Horizontal force per unit length [N/m]

Q_y Vertical force per unit length [N/m]

As can be found in the same chapter of the aforementioned book of Timoshenko and Woinowsky-Krieger

Three mean (integrated) quantities are determined for both lites and used by the structural model:

$w_{vol} = \int_0^a \int_{-b/2}^{b/2} w(x,y)dxdy$ Volume [m^3] connected to lite deviation (i.e. w integrated over x and y),

$Q_x^{iy} = \frac{1}{b}\int_{-b/2}^{b/2} Q_x(0,y)dy$ Force per unit of length [N/m] in the deflection direction on a vertical boundary,

$Q_y^{ix} = \frac{1}{a}\int_0^a Q_y(x,-\frac{b}{2})dx$ Force per unit of length [N/m] in the deflection direction on a horizontal boundary,

Which expressions are given by:

$$w_{vol} = \frac{q}{24D}\frac{ba^5}{5} + \frac{qa^4}{D}\sum_m^{\infty}(c_1 b_m \sinh(a_m) + c_2(b\cosh(a_m) - b_m \sinh(a_m)))b_m$$

$$Q_x^{iy} = -\frac{qa}{2} + \frac{2\pi^3 qa}{b}\sum_m^{\infty} m^3 c_2 b_m \sinh(a_m)$$

$$Q_y^{ix} = -2\pi^3 q\sum_m^{\infty} m^3 c_2 b_m \sinh(a_m)$$

Where in the summation m is only taken to be odd and

$$b_m = \frac{2a}{m\pi}.$$

In the structural model, the expressions w, w_{vol}, Q_x^{iy} and Q_y^{ix} are determined for both glass lites based on the (constant) load q. In these calculations there is already a provision for a coupling with the model for water vapor permeation as is discussed in the next section.

The (constant) load q for both lites is composed of the structural model based on the weight load, q_{weight}, the barometric pressure, $p_{barometric}$, the wind load, q_{wind} and the filling gas pressure p_g, (all in [Pa]) according to

$$q = p_{barometric} - p_g - q_{wind} + q_{weight}$$

In the calculation of the weight load there is provision for the azimuth and tilt angle of the IG unit. Furthermore, the wind load is determined from

$$q_{wind} = 0.5 C_{wl} \rho_{air} v_{wind}{}^2$$

Where ρ_{air} is the surrounding air density [kg/(m^3], v_{wind} is the wind speed [m/s] and the value of the constant, C_{wl} [-], depends on whether the wind direction is leeward or windward.

Coupling with Lumped Mass Balance for Gas

The applied loads in the thickness direction on both glass lites of the IG unit are linearly dependent on the total filling gas pressure p_g^{n+1} for the new time step as pointed out in the previous section. This pressure must fulfill the lumped mass balance equation for the filling gas, i.e.

$$\frac{w_{vol,g}^{n+1} p_g^{n+1} M_g^{n+1}}{R T_g^{n+1}} - \frac{w_{vol,g}^{n} p_g^{n} M_g^{n}}{R T_g^{n}} = \Delta t * flux_g$$

Where the superscript n and $n+1$ indicate the old and new time level, respectively, and

M_g is total molecular weight (in [kg/mole]) of filling gas

R is gas constant (in [J/{mole*K)]

T_g is temperature (in [K]) of filling gas

$flux_g$ is flux (in [kg/s]) of filling gas out of cavity

$w_{vol,g}$ is cavity volume (and filling gas volume) (in [m*m*m],

(Cavity volume (and filling gas volume) can be easily determined from a difference of the volumes connected to the deflections of the two lites (see previous section) and the addition of a volume that corresponds to the distance between the two lites.)

With the loads of the two glass lites linearly dependent on the filling gas pressure, it is seen from the previous section that (assuming the distance between the boundaries of the two plates to be constant per time step), among others, $w_{vol,g}$ is also linearly dependent on the filling gas pressure and hence the lumped mass balance equation reduces to a quadratic expression for p_g^{n+1}.

Therefore, the structural model can easily account for a coupling with the permeation model by calculating the coefficients of this quadratic expression in order to solve for p_g^{n+1}. With this new filling gas pressure then the values for deflection w and (mean) forces per unit length Q_x^{iy} and Q_y^{ix} can be determined. This data serves then as input for a set of spring-dashpot systems that models a typical cross section of the unit with several seals (and a metal spacer). From this set of spring-dashpot systems the typical structural response of the seals (and a metal spacer) is calculated. For example, stresses and deformations in the seals and the new distance between the glass lite boundaries are obtained from this model. These parameters are then used in a next iteration of the chain of model calculations for a time step as described above. The description of this set of spring-dashpot systems is found in Section 4.3.1.6.2.

The typical cross-section considered with the set of spring-dashpot systems cannot be really connected to a specific position in the IG unit. It should be seen as a model for the mean/maximum structural response of the seal system as only the maximum of the (mean) forces per unit length Q_x^{iy} and Q_y^{ix} serves as main input to the deformation calculations by means of the spring-dashpot systems.

The coupling between the structural model and the permeation model discussed in this section is schematically given in Figure 4.3.5. In the Figure it is seen that first there is provision for an equilibrium between the deflections of the glass lites, resulting from filling gas pressure, after which the structural response of the seals (and metal spacer) are brought in equilibrium with the lite deformations.

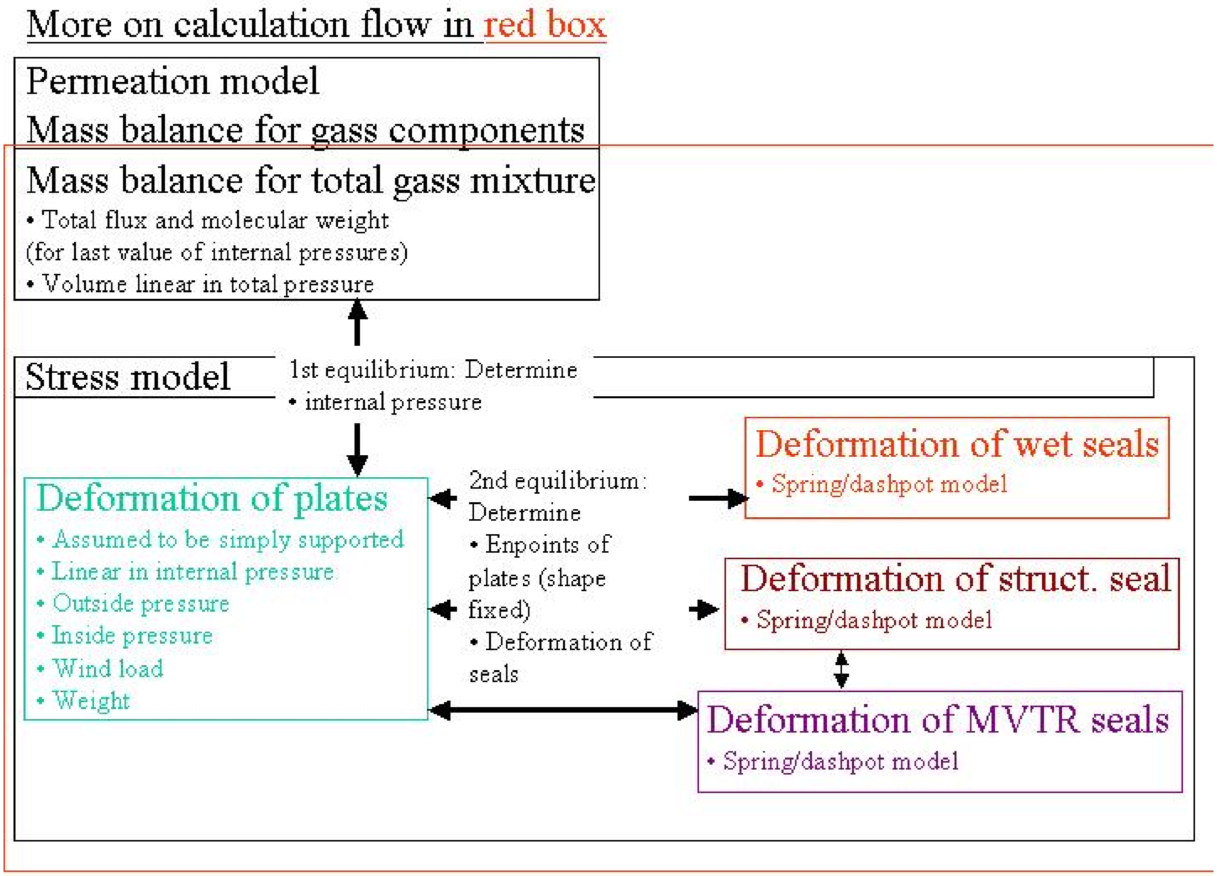


Figure 4.3.5 Structural Model Calculations (Brown box above is not complete)

Note that one of the convergence checks for the structural model is based on the residuals of the above equation of this section; *i.e*. a mass balance.

In the next section, a general explanation is given of the space behavior of the seal materials.

Visco-elastic Behavior of Polymers, General

Amorphous polymers can show a range of mechanical properties from viscous fluids to elastic solids depending on time scale, ambient temperature and diluents concentration, as can be seen in Figure 4.3.6.

The polymer changes from a “glassy Phase”, characterized by a high modulus, to a “rubbery Phase” with significantly lower modulus, as time advances, temperature and moisture content increase. Between these two is a transition “leathery Phase”; the transition is defined by the glass transition temperature. The magnitude of the glass transition temperature has been attributed to the free volume of the polymer, defined as the difference between occupied and specific volume of the polymer. The free volume increases with the diluent concentration (moisture content). An expression for the glass transition temperature proposed by Kwei providing for secondary interactions is:

$$T_g = \frac{T_{g1}W_1 + kT_{g2}W_2}{W_1 + kW_2} + qW_1W_2 .$$

Where T_g (in [K]) is the glass transition temperature of the polymer diluent mixture, W is a weight fraction, k is an adjustable parameter for free volume effects, q is an adjustable parameter for secondary interactions, 1, 2 denote polymer and diluent, and T_{g1} and T_{g2} denote reference temperatures.

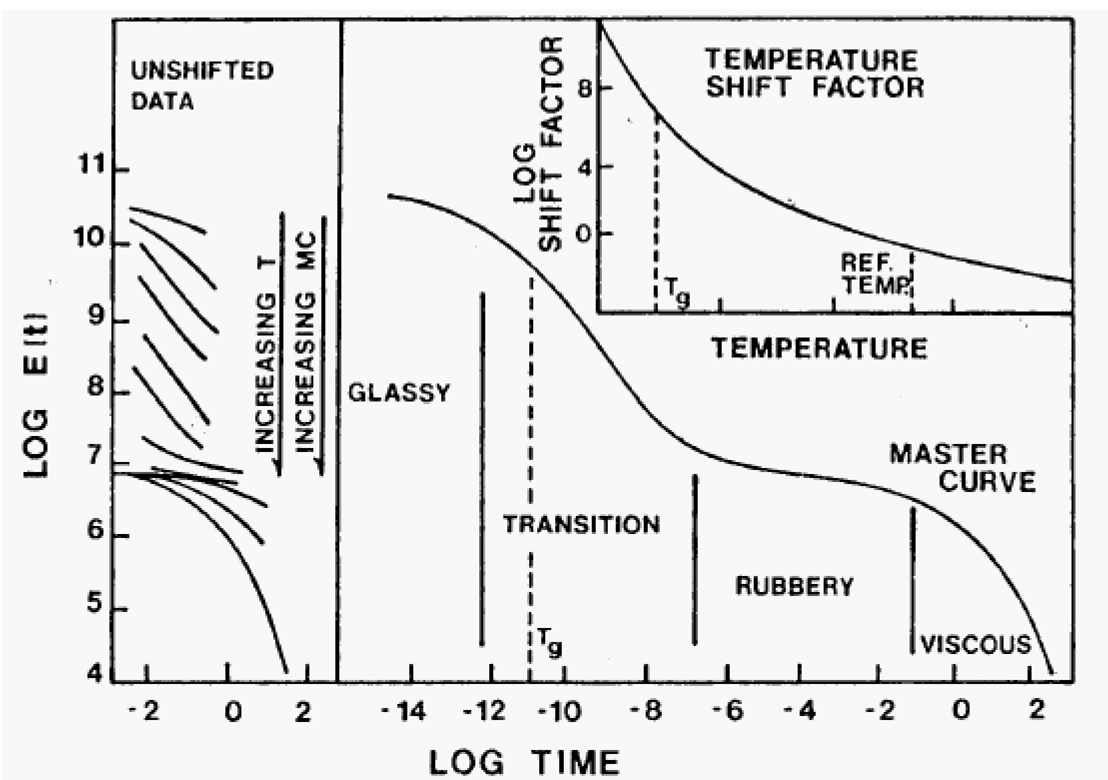


Figure 4.3.6 Typical change of relaxation modulus E(t) of an amorphous polymer with time and temperature.

In this simulation, we assume that the material is above the glass transition temperature, where the glass transition temperature is constant. The visco-elastic properties can be represented by the creep:

D(t) (ε=σD(T)), $D(t)(\varepsilon = \sigma D(T))$

or relaxation modulus

$\sigma = \varepsilon E(T)$

Time-Temperature Equivalence of Visco-elastic Properties

In general, a time-temperature equivalence of the visco-elastic properties is observed [Williams-Ferry]. The basis of this principle is that temperature accelerates the time-dependent response of the material. Accelerated testing methods are based on this equivalence principle. The time-dependent material properties are determined at different temperature levels and shifted horizontally along the log time axis through a time multiplier (shift factor), until a smooth curve is obtained. This is the so-called "master curve". The "master curve" describes the time dependence of the investigated property at a reference temperature. The property at other temperatures is calculated from the "master curve" with the reduced time principle, or shift factor. The observation of the time-temperature superposition was in the first instance empirically observed. Later a theoretical basis was developed where the temperature shift factors can be calculated on the free volume concept. When the glass transition temperature of the polymer is chosen as the reference temperature, the temperature shift factor can be determined above T_g by the Williams-Landell Ferry (WLF) equation (below T_g, an Arrhenius type equation is appropriate).

$$\log(a(t)) = \frac{-C_1(T-T_g)}{C_2+T-T_g}$$

Where the constants C_1 (in [-]) and C_2 (in [K]) of the WLF equation, after being determined experimentally for several polymers, were defined as "universal" constants for cases where experimental validation is not feasible (C_1=17.44, C_2=52.1).

Mathematical Representation of Visco-elastic Behavior

According to linear visco-elastic theory, the time dependent response of a visco-elastic material, for an arbitrary loading history, can be expressed either in an integral or differential form, if a single creep (or relaxation) curve is available for a prolonged time period (e.g. experimentally collected). The (convolution) integral representation is based on the superposition principle, where the effect of a complex loading history can be equated to the sum of independent contributions of smaller load steps, the so called Boltzmann Superposition Integral. For creep this reads (similar for stress relaxation) as

$$\varepsilon(t) = D(t)\sigma(0) + \int_0^t D(t-\varepsilon)\frac{d\sigma}{d\varepsilon}(\varepsilon)d\varepsilon$$

The differential form is based on mechanical analogies, such as combined spring and dashpot systems. Creep behavior in its simplest form is described by a spring and dashpot in parallel, a Kelvin element,

$$\frac{d\varepsilon}{dt} = \frac{D_0}{\tau}\sigma - \frac{1}{\tau_0}\varepsilon$$

Where τ_0=η/E retardation or relaxation time, D_0 the compliance of the spring, E the modulus of the spring, η the viscosity of the dashpot, D the compliance of the spring, '0' denotes a specific reference temperature. The time dependent response of a Kelvin element for a step load reads as

$$\varepsilon(t) = \sigma(0)D(t)$$

Where

$$D(t) = D_0(1 - e^{-t/\tau_0})$$

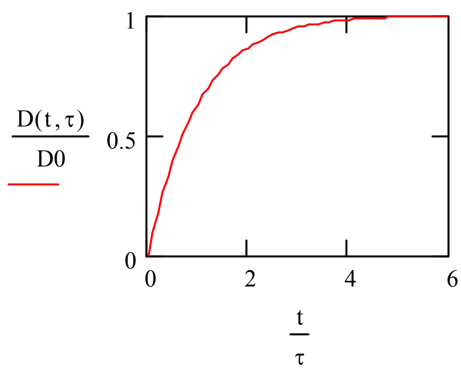


Figure 4.3.7 Time Dependent Response of a Kelvin Element for a Step Load

Relaxation behavior is described by a Maxwell element, a spring and dashpot in series. Description of more complex material behavior can be obtained by combinations of Kelvin and Maxwell elements. In the next section, the system of springs and dashpots is described that was used to model the material behavior and deformations of the seals and metal spacer of the IG unit.

Spring - Dashpot Systems for Seals and Metal Spacers

Geometry

The configuration of the sash-seals-spacer-lites system is depicted below for two classes of IG units: TPS systems (without spacer) and Box-Spacer systems.

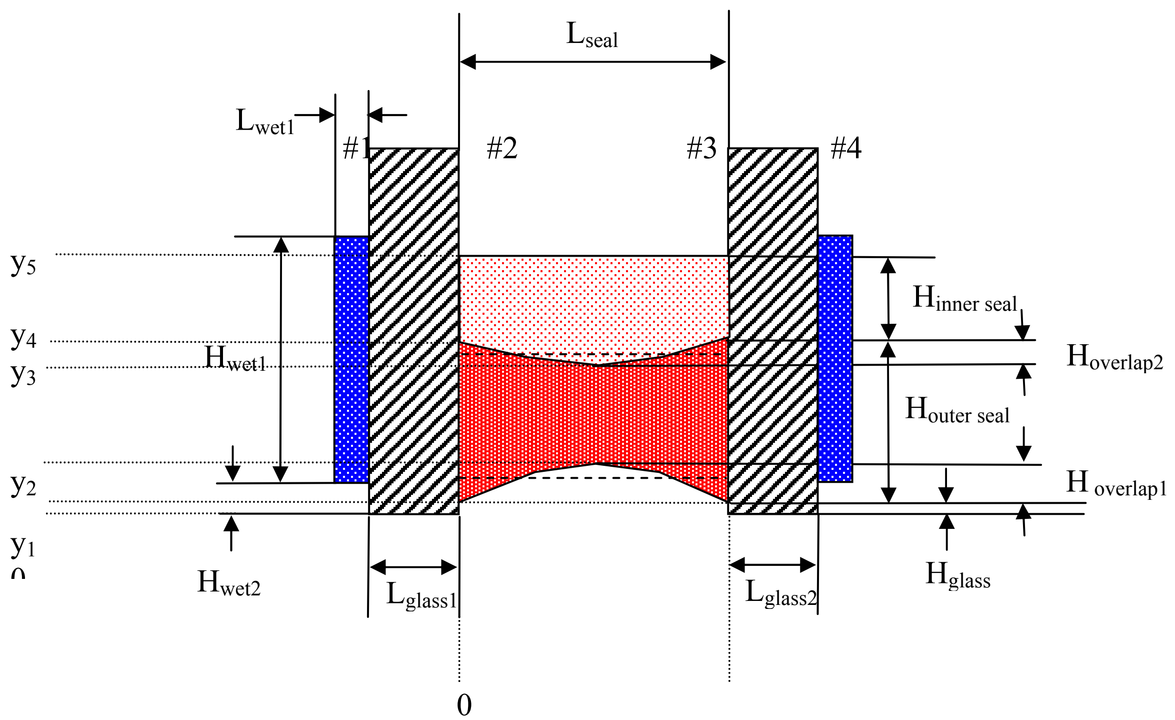


Figure 4.3.8 Thermal Plastic Spacer (TPS) System

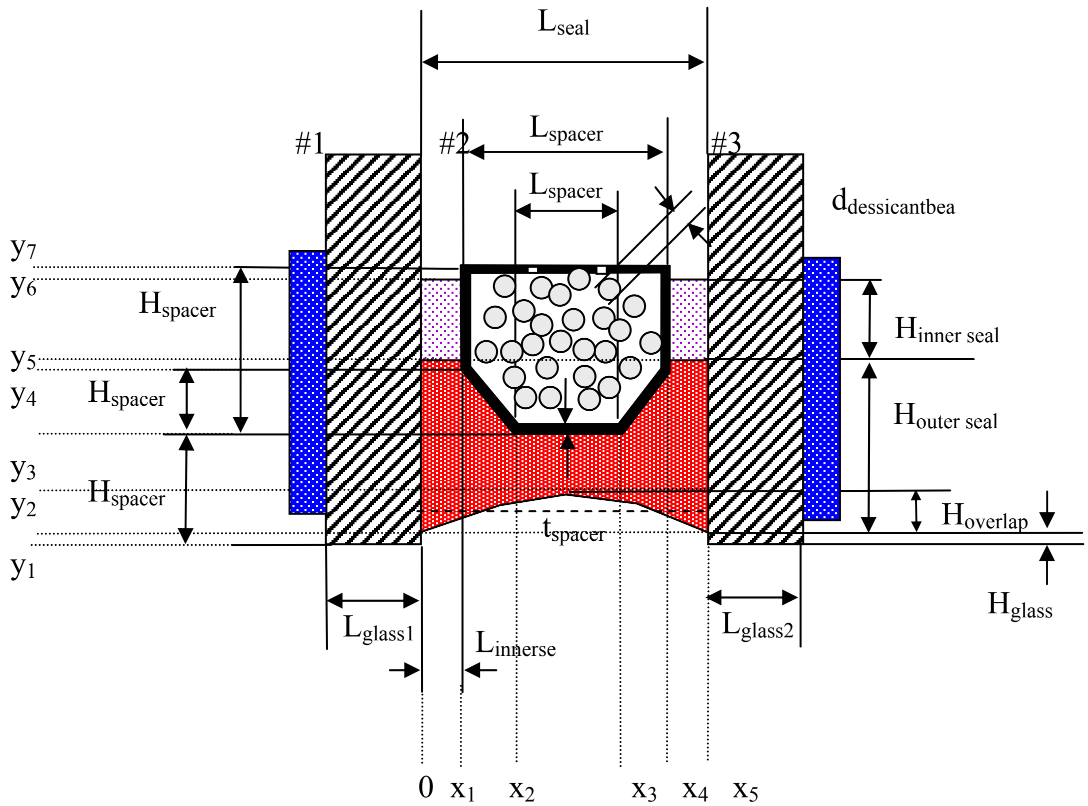


Figure 4 3.9 Box Spacer System

Model Description

To describe the mechanical behavior of the TPS-system and Box-Spacer system, the components are represented by mechanical elements built up from springs (representing elastic behavior) and dashpots (representing viscous/damping behavior). The metal spacer in the box-spacer system is treated as a purely elastic component, whereas the seals are, in principle, visco-elastic components. Each visco-elastic component is modeled by a single-mode Kelvin-Voigt element, which is suited for describing the effects of creep, i.e., the time-dependent change in strain due to the application of a stress (caused by the load forces exerted by the glass window lites on the system). This is all reflected in the two figures below for both normal and shear loading for the Box-Spacer System. As the stiffness of the glass window lites are considered infinitely large compared to the stiffness of the other elements, the lites are not represented by mechanical elements.

Concerning the loading of the system, a distinction is made between normal loading (i.e., normal to the glass window lites) and shear loading (i.e., in the direction parallel to the glass window lites).

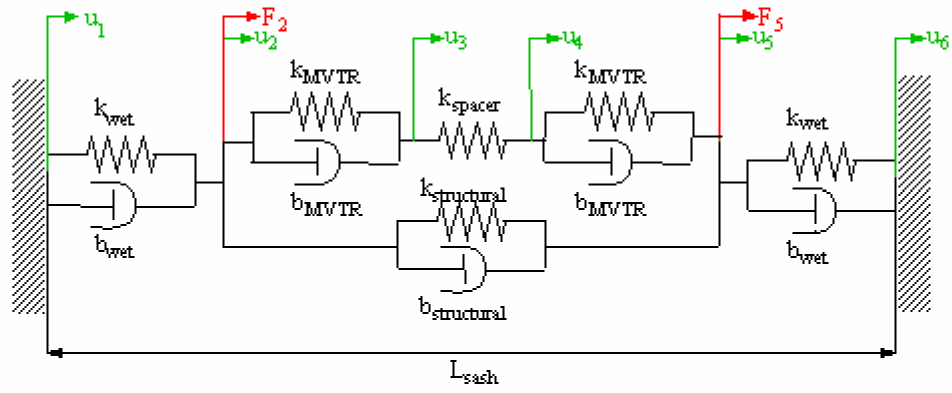


Figure 4.3.10 Spring-Dashpot System for Normal Loading of Box-Spacer System

- Normal loading originates from three sources:
- Normal loads exerted by the glass window lites on the system which are due to the lite deflections in the lite thickness direction, i.e. the maximum of Q_x^{iy} and Q_y^{ix}
- Thermal expansion of the sash in the normal direction
- Thermal expansions of the seals and spacer in the normal direction

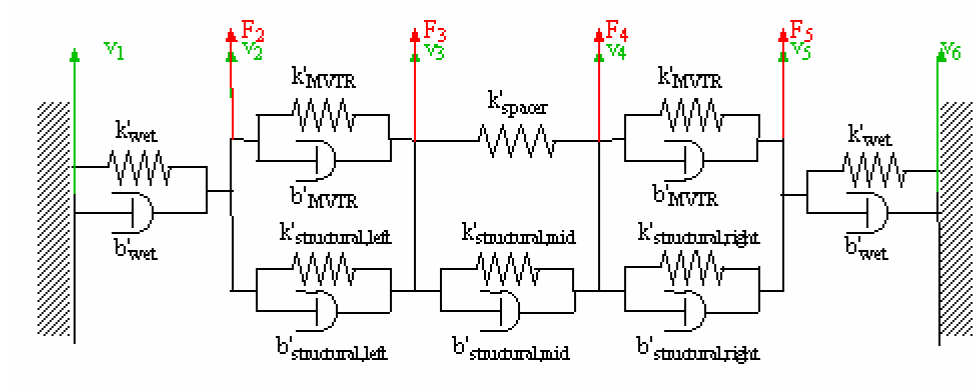


Figure 4.3.11 Spring-Dashpot System for Shear Loading of Box-Spacer System

- Shear loading can be attributed to three sources as well:
- Shearing loads exerted by the glass lites on the system due to their weight
- Shearing load exerted by the difference between filling gas pressure and ambient air pressure
- Differences in thermal expansion in shear direction of glass lites, sash, and spacer.

Because of the shearing load caused by the spacer, the structural seal in a Box-Spacer System is split into three parts, of which the two outer parts have a 'length' (measured perpendicular to the glass window lite) that is equal to the length of the MVTR seal.

All spring and dashpot constants are calculated from Young's moduli, Poisson's ratios and dynamic viscosity of the seal materials as well from the seal dimensions. Note that the spring and dashpot constants *k* (and *b*) for normal loading differ form the constants *k'* (and *b'*) for shear loading, as the constants for normal loading are determined from Young's modulus and the constants for shear loading are determined from the shear modulus (in [Pa])

$$G = \frac{E}{2(1+\nu)}$$

Whereas most material parameters can be prescribed by the user as linear functions of time and temperature, the temperature dependence of relaxation times for the seals (defined as the ratio of dynamic viscosity and Young's modulus) is described by the established WLF-equation, which is generally valid for the temperature range from Tg (the glass transition temperature) up to T_g + 100°C.

The systems that are ultimately calculated for each time step and for each loading type can be represented as

$$B\dot{u} + Ku = f\,,$$

In which u is the vector of displacements, B and K are the damping and stiffness matrix, and f is the load vector.

Influence of Bending of Glass Window Lites on Seals

Due to the external loads, the glass lites may be subject to bending (either inward or outward), thereby causing a difference in the extensions of the innermost and outermost seals between the two lites. It is assumed here that the bending of the lites is a result of the external loads only, and is not caused by the difference in stiffness between the innermost and outermost seal. The bending of a lite is given by its angle φ_{pane} with respect to the axis along the un-deformed lite length

$$\varphi_{pane} = \arctan(w'_{pane})\,,$$

Where w'_{pane} is the derivative of the glass lite deflection w_{pane} that can be easily determined from the expression for the deflection given above.

The bending of the lites can be taken into accounted by a modification of the force balance in the set of springs and dashpots as explained for the TPS design and shown in Figure 4.3.12.

The bending of the lite causes extra displacements $u_{MVTR,extra}$ and $u_{struc,extra}$ at nodes 2 and 3 in the set of spring dashpots given by

$$u_{MVTR,extra} = a_{MVTR} \sin(\varphi_{pane})$$
$$u_{struc,extra} = a_{struc} \sin(\varphi_{pane})$$

The a_{MVTR} and a_{struc} terms are offset distances of the points of action for the forces on the seals relative to the point of action of the force on the wet seals. Note that a_{struc} has a negative value, as it is applied in the downward direction.

The net result of the bending of the lite on the reaction forces should be zero. To accomplish this, the displacement u_2 and u_3 (and their time derivatives) in the original system of equations should be replaced by 'new' displacements u^*_2 and u^*_3 that are given by

$$u_i^* = u_i + a_i \sin(\varphi_{pane})$$
$$\dot{u}_i^* = \dot{u}_i + a_i \cos(\varphi_{pane})\dot{\varphi}_{pane},$$

With 'i' = [struc, MVTR, wet], $a_{wet} = 0$ and φ_{pane} the bending angle of the lite at node 2 or 3. This means that the system of equations has to be modified to

$$B\dot{u} + Ku = f - Ba^T \dot{u}' - Ka^T u',$$

Where '*a'* is an array with point of action offsets,

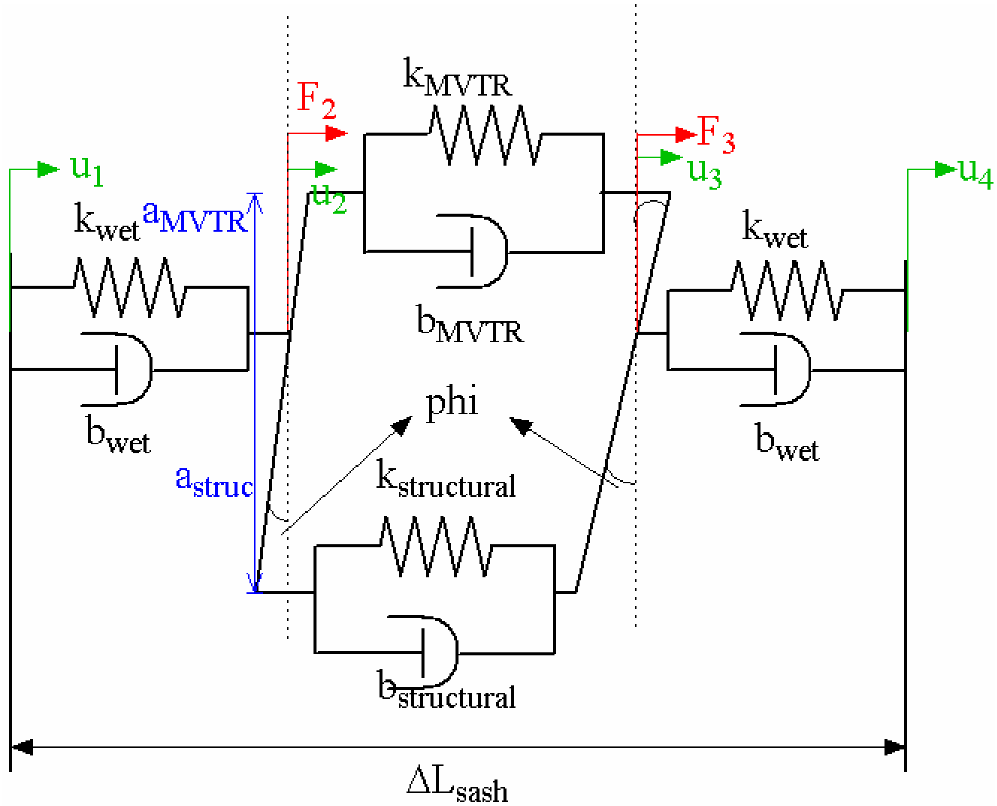


Figure 4.3.12 Bending in set of Spring-Dashpot Systems for TPS Design

Input and Output Data

Apart from the material data and component dimensions that have been defined through the input file, the following data serves as the main input for the spring-dashpot calculations

- The type of IG unit (TPS or box-spacer)
- The time at the current time step, at the previous time step and at the start

- Mean values for the loads in normal and shear directions exerted by the glass window lites on the seal systems, including the load due to the weight of the glass lites.

- The temperatures of the system components at current and previous time step.

- The calculated displacements at the previous time step and previous iteration

- The derivatives of the glass lite displacements (representing the bending of the lites)

Among the results that are determined are:

- The effective (Hubert-Hanky) stresses in the seal components (in [Pa])

- The displacements (in [m]) in the set of spring-dashpot systems, from which, for example, the distance between the lites can be updated

- The strains and shears of the system components (dimensionless)

- The residuals of the solved systems (in [N/m])

This effective stresses in the seal components given by:

$$\sigma_{eff} = \sqrt{\sigma^2 + 3\tau^2}$$

And is determined from the normal stress σ and shear stress τ for the component.
Residuals indicate convergence of the solution within an iteration loop and are calculated as

$$f_{current} - B_{current}\left(\frac{u - u_{old}}{\Delta t}\right) - K\left(u - u_{old}\right).$$

With u the most recent solution obtained for the current time step. This residual has the dimension of load per unit length as all (external) forces in the system are per unit length.

Chain of Structural Model Calculations

For a specific time-step and sub-iteration, the following chain of structural model calculations is performed:

1) Based on a unity load and updated material parameters for the glass lites, their deflection and derived data is determined

2) With some of this data, and the actual loads for the lites, the coefficients for the quadratic equation for the new gas filling pressure are determined

3) From these coefficients the pressure is calculated, from which the total loads for the lites can be determined such that the actual deflection and its derived data are determined

4) Subsequently the external normal and shear loads for the system of seals can be found

5) Based on actual time, actual temperature, etc., all visco-elastic (spring-dashpot) constants are updated

6) Based on the new temperatures, the thermal expansion of the components is determined and transferred to equivalent loads

7) Seal deformations (i.e., displacements) for the normal loading situation are determined and the residuals (for the previous displacements found) are updated

8) Seal deformations (i.e., displacements) for the shear loading situation are determined and the residuals (for the previous displacements found) are updated

9) From the seal deformations found, seal strains and stresses are calculated.

Coupling of the Physical Models, Iterative Procedure

A flow chart of the simulation is shown below in Figure 4.3.13. The sub-models are coupled, i.e., a change in gap width results in the heat flow, causing a change in glass surface temperatures, the gas in the gas space contracts or expands, resulting in change in pressure difference over the glass lites, affecting the gap width, etc. An iterative procedure is used to solve the various equations of the sub models. Within a time step, the sub-models are repeatedly called one by one, and when new information becomes available about temperatures, pressures, deflections, material properties, etc., the old values are replaced with the new values, and the process continues until the values no longer change significantly per sub-iteration. In this case, the sub-models are considered converged, after which the simulation will proceed to the next time step.

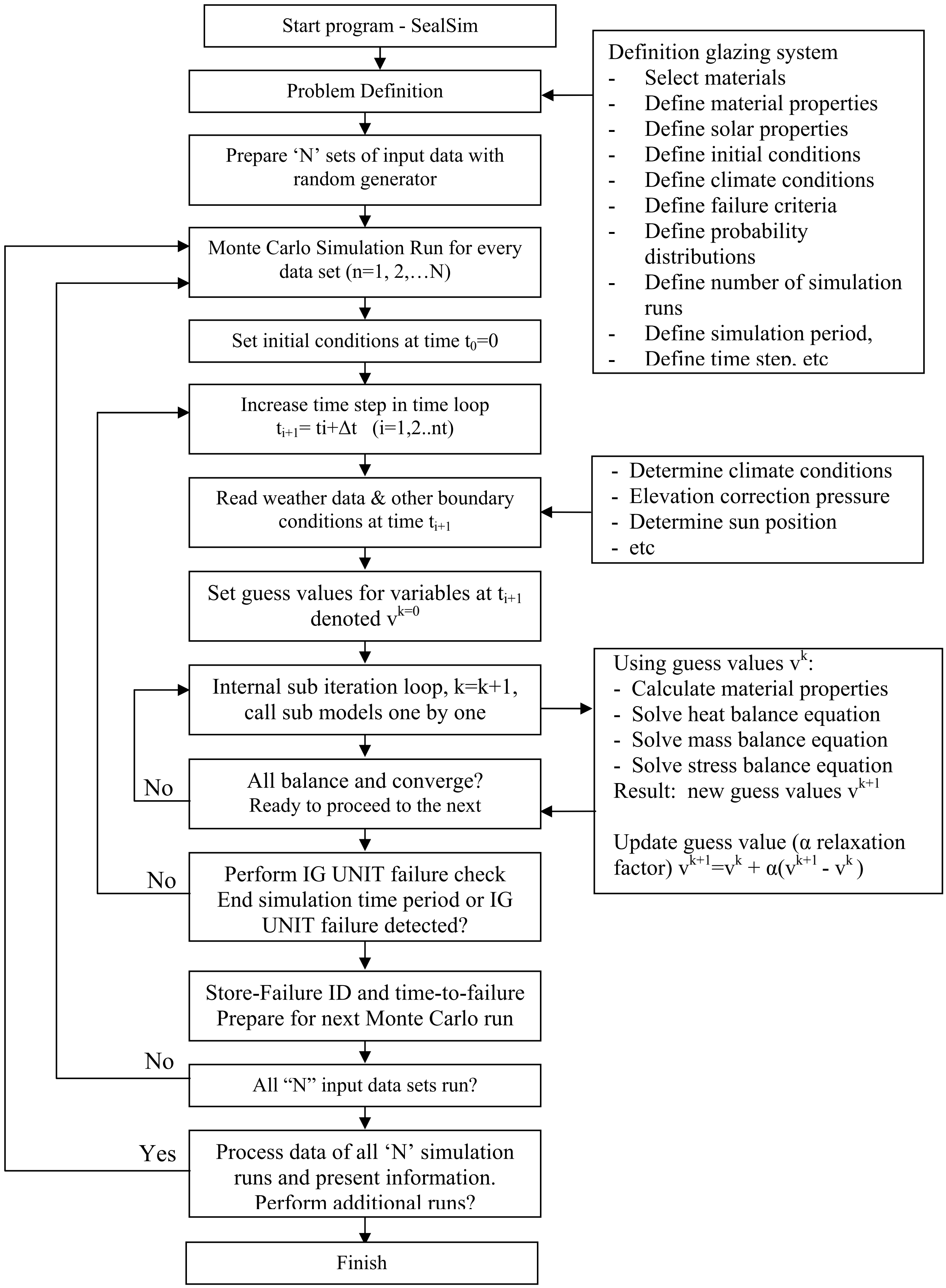


Figure 4.3.13 Flow Chart for Simulation

Calculation Procedure 'SealSim'

A complete description of the calculation procedure shown in Figure 4.3.13 follows:

- **STEP 1. Problem Definition**
  - Define glazing system
    - Define dimensions of glass and seal
    - Window orientation (tilt, azimuth)
    - Characteristics building/terrain (to calculate wind force)
    - Define permeation shortcuts due to corner keys etc.

  - Select materials
    - Select glass lites numbers 1 and 2
    - Select outer seal polymer material
    - Select inner seal polymer material
    - Select desiccant present in inner seal (TPS System)
    - Select desiccant present in spacer (Box Spacer System)
    - Define which fill gases are present and are involved in permeation
    - Select frame material

  - Define material properties
    - Define solid material properties
    - Define polymer material properties
    - Define desiccant material properties
    - Define fill gases and gases involved in permeation
    - Material properties are defined in the materials database (sealsim.mdb).
      - Note: This file can be edited with the program Microsoft Access

- Define solar properties
  - Read solar properties individual glass lites number 1 and 2 at normal incidence
  - Emissivities of the glass lites (long wave)
  - Extrapolation of solar properties to any angle of incidence
  - Properties are defined in glazing-database (GlazingTPD.mdb).
    - Note: This file is protected and cannot be edited).

- Define initial conditions (filling conditions)
  - Temperature (uniform)
  - Total pressure gas space
  - Barometric pressure outside and inside (no wind load assumed)
  - Volume fraction (mole fraction) or partial pressure of gases
  - Amount of desiccant present
  - Initial concentration of adsorbent in the desiccant
  - Initial concentration of adsorbent in the polymer
  - Initial seal length at filling, stress free

- Define climate conditions
  - Select weather station and climate period. The data in the TMY2 file contain station location and elevation. Note: IG unit elevation assumed to the station elevation unless explicitly defined in extended TMY2 format
  - Terrain characteristics at the weather station, anemometer height
  - Note that during transport from production location to final location, the climate conditions (including barometric pressure etc) in general will change. It is assumed that this is accounted for in the weather file. This means that if existing weather data of a station are used, weather data during transport has to be inserted in this data file.

        - Climate next to seal is the same as weather station climate, unless explicitly defined as a function of time in a separate data file

- Define simulation time
    - Simulation start date and time
    - Simulation end date and time
    - Define (numerical) time step

- Define failure criteria
    - Define threshold levels at which IG unit fails, e.g. the IG unit fails when internal condensation occurs.
    - Cohesive failure properties come from the database (can have a probability distribution)

- Define numerical settings
    - Iterative loop through individual balance equations
    - Define convergence criteria and relaxation factors.

- Define probability distribution and number of Monte-Carlo runs "N"
    - The material-parameters-failure criteria can have (1) "fixed" values or (2) a probability distribution (in case of a normal distribution: mean value and standard deviation). It is up to the user to decide this.
    - A simulation run, however, takes only fixed values as input. Before simulation starts, therefore, a random generator determines a fixed set of values, and then runs a simulation. By repeating this procedure several times, the results of these simulation runs can be statistically evaluated. The user specifies the total number of simulation runs, and it is up to the user to judge if this gives a statistically relevant output (only for a linear model can it be decided how many runs are

required beforehand to give certain output accuracies, see documentation elsewhere).

- **STEP 2. Prepare 'N' sets of input data with random generator**

- **STEP 3. Perform Monte Carlo Simulation Run for each set of input data (n=1,2..N)**
    - Set initial conditions IG unit (filling conditions)
        - Specify initial conditions of IG UNIT at time zero $t_0=0$
        - For a given barometric pressure, initial gas composition and gas space pressure & temperature, calculate initial glass lite deflection and seal deflection (hence effective volume of the gas space)

    - Time loop
        - Determine current time $t_{i+1}= t_i+\Delta t$ (i=1,2..nt)
        - Read weather data TMY2 at current time step, calculate angle of incidence of the sun on the window, correct pressure for window elevation differing from station elevation and correct wind speed for meteorological conditions and building conditions (terrain etc)
        - Determine environmental conditions near seal, equal to environmental weather conditions or read from file
        - Set values of variables at last time step as estimation values for variables at current time step
            - Note about variables: Two types of variables are discerned, primary and secondary variables. Primary variables are temperature (heat balance equation), gas pressure and composition (mass balance equation components extended with Equation Of State EOS, in this case the 'ideal gas' law), and stresses and strains (deflections). Secondary variables are variables that are direct functions of the primary variables, for example gas conductivity is a (known) function of

pressure, temperature and gas composition, the characteristic heat transfer coefficient is a function of length scale, temperature, pressure, etc. During the numerical resolution process a relaxation factor can be introduced for primary and secondary variables. A relaxation factor for primary variables is preferred.

- Iteration loop

  Internal iterations loop through individual balance equations to update estimated values:

  - Solve heat balance equation
    - Calculate new estimated temperatures in the IG unit (using old estimates for temperature, average gas gap width between glass lites for heat transfer, material properties, etc), essential center of glass calculation 1D
    - Calculate seal temperature or read data from file (time data)

  - Solve mass balance equation for gas components, subdivided into three parts
    - Permeation inner & outer seal
      - Calculate amount and composition of gas entering/leaving the gas space through inner & outer seal (using old estimates for volume gas space, gas composition, gas pressures etc)
      - Last item is area-weighted summation of two one dimensional paths (1) inner & outer seal present (2) inner seal missing.
      - Calculate how much gas is absorbed in desiccant (using old estimates for composition and pressure gas space)

        - Mass balance in the gas space
            - Calculate new value for gas space pressure and gas composition.

        - Stress model, solve force balance
            - Calculate new stresses and deflections of the glass lites and seals, based on
                - Boundary conditions: prescribed sash displacement, thermal expansion of the spacer bar
                - Most recent estimates for gas space pressure, temperature, etc.

        - Update estimate for variables using under-relaxation.
        - Update material properties (according to new estimate temperatures, etc.)
        - Loop through individual balance equations and update variable values until convergence of all balance equations is obtained (within preset error limit). If divergence is detected, restart iteration loop with more conservative relaxation factors.

    - Go to the next time step and repeat the procedure until the IG unit failure criteria is encountered or user indicated simulation time period is exceeded
    - Store data

- End time loop

    - Stop simulation if simulation time period is exceeded or an IG unit failure criterion is encountered.

- At interrupt, store data about current simulation run ‘n’.
- Present statistical information for run 1 to ‘n: how runs met criteria, how many runs were encountered for which a failure criterion occurred and the average lifetime, with standard deviation, of each failure criterion.

- Start another durability simulation until ‘N’ sets of input data are simulated (or break simulation on user interrupt).
  - *Example, simulation time 10 years, 16 runs, results:*
  - *Run 1: no failure, hence service life of 10 years or more*
  - *Run 2: failure after 5 years, due to failure criterion no 2*
  - *Run 3: failure after 4 years, due to failure criterion no 1*
  - *Run 4: failure after 6 years, due to failure criterion no 2*
  - *Run 5: failure after 7 years, due to failure criterion no 2*
  - *Run 6-16: no failure, hence service life of 10 years or more*

- *Statistical interpretation*
  - *The average service life is (12x10yr+5yr+4yr+6yr+7yr)/16 = 8.875 years or more*
  - *75% of IG unit’s do have a service life expectancy of 10 years or more*
  - *25% of the IG unit’s fail within 10 years*
  - *The IG unit’s that fail, fail after on average 5.5 years (sigma=1.29)*

- *Of IG unit’s that fail:*
  - *75% fail due to criterion no 2, on average after 6 years (standard deviation=1)*
  - *25% fail due to criterion no 1, on average after 4 years (standard deviation=0)*

- **STEP 4. End simulation**

- 4.1. Process data
  - Process the data of all simulation runs (# passed, # failures + mean/standard deviation lifetime)
  - Present information
  - Depending on outcome, decide not to end simulation, but do perform additional Monte-Carlo runs, go to step (2) again.

- 4.2. End simulation
  - End simulation, if it is decided not to perform additional Monte-Carlo runs.

4.4 Materials Databases

4.4.1 Introduction

The properties for the materials used by the simulation are kept in two databases**:** **"sealsim.mdb,"** and **"GlazingTPD.mdb."** The **"sealsim.mdb"** is a database developed for the project containing the physical properties of the sealants, spacer, sash glass, gases and desiccants. **"GlazingTPD.mdb"** is a modified version of the International Glazing Database (IGDB), and provides the optical properties for the glass used in the simulation.
The **"sealsim.mdb"** materials database was created in a Microsoft® Access[1] format and contains the material properties necessary to carryout the calculations used in the simulation. The tables created in the database are:

"Desiccant Materials"
"Gases Table"
"Gas Through Desiccant Props"

[1] Microsoft® Access is a registered trademark of Microsoft.

“Gas Through Seal Props”

“Polymer Materials”

“Solid Materials”

A description of the tables in the database is given below:

Desiccant Materials

The “**Desiccant Materials**” table contains data on properties of the desiccants. These materials would include molecular sieves (bead and powder) and silica gel. Desiccant beads used with box spacers and desiccant powders used with the thermal plastic spacer system are selected from this database using the GUI. The material properties of the desiccants are used by the permeation model to determine the amount of desiccant present in the simulated IG UNIT and to determine some of the permeation parameters. Material properties in the **“Desiccant Materials”** table are:

Bulk Density

True Density

Tortuosity Factor

Bead Size

Pore Size

Porosity

Gases Table

The “Gases Table” contains gas properties used by the thermal model. These properties are for the ten gases (H_2O, N_2, O_2, Ar, Kr, Xe, SF_6, Gas8, Gas9 and Gas10) that can be used by the simulation. Material properties in the “Gases Table” are:

Molecular Weight

Thermal Conductivity

Dynamic Viscosity
Heat Capacity

The values of thermal conductivity, dynamic viscosity and heat capacity are dependent on the temperature of the gas. The "Gases Table" contains the appropriate coefficients (a, b and c) for thermal conductivity, dynamic viscosity and heat capacity, allowing the simulation to calculate their value as a function of temperature using the general equation:

$$\text{Property}(T) = a+bT+cT^2$$

Gas Through Desiccant Props

The "Gas Through Desiccant Props" table contains the gas adsorption properties (including water vapor) on the desiccants and is used by the permeation model. Properties in the "Gas Through Desiccant Props" table are:

Adsorption Coefficients (at two reference temperatures)
Maximum Loading
The adsorption coefficient and maximum loading are needed for each individual gas for each desiccant used in the simulation.

Gas Through Seal Props

The "Gas Through Seal Props" table contains the properties used by the permeation model to determine the mass transport of gases (including water vapor) through the inner and outer sealants. Material properties in the "Gas Through Seal Props" table are:

Solubility (at two reference temperatures)
Permeability (at two reference temperatures)

The solubility and permeability are needed for each individual gas in each sealant material used in the simulation.

"Polymer Materials"

The Polymer Materials table contains the structural properties of the IG UNIT sealants (inner and outer) as well as the glazing sealant (wet seal) used to mount the IG UNIT to the window sash. Such materials would include sealants based on polysulfide, polyurethane, silicone or polyisobutlyene (PIB). Each material in the table is identified by "TRUE" or "FALSE" statement in appropriate column as to whether it is available to the simulation as an inner, an outer or a wet seal. Material properties in the "Polymer Materials" table are:

Thermal Conductivity
Heat Capacity
Density
Emissivity
Cohesive Yield Stress
Minimum Strain
Maximum Strain
Maximum Shear
Young's Modulus
Poisson Modulus
Coefficient of Thermal Expansion
Dynamic Viscosity
Glass Transition Temperature
WLF constants c_1^g and c_2^g

The model allows several of the properties (yield stress, minimum and maximum strain, maximum shear, Young's and Poisson moduli and the coefficient of thermal expansion) to vary as a function of temperature (T) and time (t), allowing the simulation to calculate their value using the general equation:

$$X(T,t) = X_O + XTempCoef \cdot (T - X\,\mathrm{RefTe}\,mp) + XTimeCoef \cdot t$$

Solid Materials

The “Solid Materials” table contains the properties of the glass, spacer and sash materials. Each material in the table is identified by “TRUE” or “FALSE” statement in appropriate column as to whether it is available to the simulation as a glass, a spacer or a sash material. Material properties in the “Solid Materials” table are:

Thermal Conductivity
Heat Capacity
Density
Emissivity
Cohesive Yield Stress
Minimum Strain
Maximum Strain
Maximum Shear
Young’s Modulus
Poisson Modulus
Coefficient of Thermal Expansion
Solar Absorption Coefficient

The model allows several of the properties (yield stress, minimum and maximum strain, maximum shear, Young’s and Poisson moduli and the coefficient of thermal expansion) to vary as a function of temperature (T) and time (t), allowing the simulation to calculate their value using the general equation:

$$X(T,t) = X_O + XTempCoef \cdot (T - XRefTemp) + XTimeCoef \cdot t$$

4.4.2 Database Modification

The materials database, "sealsim.mdb", is not protected. Using the program "Microsoft Access" data in the database can be edited by the user and new materials can be added to any of the tables. The only restriction is that the simulation is limited to ten gases. The first seven of these gases have been assigned to water vapor (H_2O), nitrogen (N_2), oxygen (O_2), argon (Ar), krypton (Kr), xenon (Xe) and sulfur hexafluoride (SF_6). Three additional gases, identified in the GUI as Gas8, Gas9 and Gas10 are available for the user to define.
When modifying the database, it is important to enter new data that is calculated in the appropriate units. A complete listing of the units associated with each of the material properties can be found in the Appendix 3.

4.4.3 Interfacial Properties

The interfacial properties used by the simulation, such as the adhesive strength of the outer sealant to the glass, are a function of the two materials involved (e.g. glass and sealant) and are not included in the materials database. These values are entered via the GUI and include:

Inner Seal – Glass Adhesion
Outer Seal - Glass Adhesion
Inner Seal – Spacer Adhesion (Box Spacer)
Outer Seal – Spacer Adhesion (Box Spacer)

In addition to entering the value for the adhesive strength of these bonds, terms can be input to account for the effect of temperature and time on the adhesive strength.

4.4.4 Glazing Database GlazingTPD.mdb

GlazingTPD.mdb is a modified version of the International Glazing Database (IGDB), which is maintained by the Lawrence Berkeley National Laboratory (LBNL)[2]. The IGDB contains the optical properties of over 1400 glazing products that can be selected for use in the simulation. For use in the simulation, the IGDB was modified by LBNL with the addition of a query used to extract the data needed for the calculations in the thermal model, including:

Glass Thickness
Solar Transmittance
Solar Reflectance of glass, sides 1 and 2
Infrared Emittance (long wave) of glass, sides 1 and 2
Thermal Conductivity

4.4.5 Material and Quality Considerations and IG Durability

As referenced in the program users' manual and the preceding sections, although not widely implemented in the program at this time, the program has the capability and flexibility to accept defined distributions representing the variance of induced stresses on the IG system and IG system strengths. As this opportunity is implemented a much more realistic response of IG life will be achieved.

Truly understanding the durability attributes of an IG system or any system requires that material and process variances be considered. In many cases, although the existence of variances are recognized, this task was simplified as representative mathematical distributions are extremely cumbersome. The simplification is done by including a worst case or average, strength and engineering or design calculations. This is currently being done with the sensitivity and debugging activities as the durability code continues to develop.

[2] Information on the International Glazing Database can be found at http://windows.lbl.gov/materials/IGDB/default.htm

The IG system strengths are represented by the component or material strengths which are input as material properties in the databases presented above. As is well known and discussed in the Phase I report, there are variances in natural or raw materials, in processing of these materials, in the application (assembly) of materials, etc. Thus, we can expect these material and process variances to create variances in the material-strength properties, material-interface properties and the response of the system. These variances can, and usually are, then understood experimentally until a mathematical distribution closely approximating the variances can be developed. These distributions (mathematical equations) represent a more realistic expectation of the material's strength properties. Even under the tightest of processing controls, variance will exist.

In addition, as consideration was given to the initial database population process, it was discovered that much less material property data was available, or would be made available, specific to common IG materials. In addition, much of the insulation glass supply chain described (through published material-specifications) their products using different material attributes and units making even a high level material comparison difficult. Listing the possible material attributes, both static and dynamic that could play a part in IG durability also produced concern that the material properties commonly used for design, purchasing, quality control, etc. may not be complete. Currently, the durability tool and the general design and application of IG materials contains a fairly large set of assumptions that could have an effect on IG durability with no specific published data supporting the assumptions one way or the other.

While most of the examples presented in the Phase 1 report and discussed here are related to material strength vs. input stress, IG assembly processes can be represented in the same way. The IG design and engineering specification for the processing of incoming glass (cutting, handling, heat treating, coating, etc.) through the final gas fill and press have variance. Each IG manufacturer will have a unique set of process variances dependent on chosen IG design, materials and process method. A highly automated process will have a different set of variances than that of a highly labor intensive process of assembly.

In the current version of the simulation program, material and process variance can be simulated by adjusting material properties presented in the material database. Thus, investigating a process variance will require a thorough knowledge of the process, associated materials, interfaces, etc. For example, the glass cutting process can leave undesirable glass edge chipping, creating stress concentrators which will cause premature glass fracturing. This process or quality characteristic can be crudely modeled in the current simulation by adjusting a glass strength property making a possible edge fracture and crack propagation more likely to occur under stress. Thus, a material property adjustment represents a process procedure with less than desirable quality control. Or, in the case of sealant or adhesive application, adjusting one or more material properties can represent the application of the material to dirty glass caused by an undesirable washing or handling process. If a single property value is being used in the calculation or a distribution representing material property variation, property adjustments can be made to represent process or quality variance. In this manner, the program can provide a feel for the sensitivity of these types of process and quality variances. It must be noted that the current program output will only provide a general trend of increasing or decreasing IG failure rates based on the process or quality attribute being investigated.

As the simulation continues to develop, process variation can be implemented. This, of course, will be a set of unique distributions dependent on the particular manufacturing methods for IG assembly. Each process will need to be investigated, variances discovered and mathematical algorithms developed to relate these manufacturing inconsistencies to the strengths of the system.

The large volume of current IG units are manufactured with a fairly limited set of designs and use a fairly limited set of material groups, many of these materials were originally developed for products completely unrelated to IG application. As IG designs and technologies advance, the set of materials and subsystems will continue to grow and will be specifically developed for IG applications. This process will insure at least two things. First, with each newly integrated technology an additional set of variances must be considered; and second, materials and their specification will be developed specifically to meet IG requirements and expectations, including durability. In fact this process has been well underway as plastics have been used for spacer bars, thermoplastic spacer systems are extruded directly on the glass lites, etc. Although the current designs represent limited groups of materials, the variation in materials offered in these groups is extensive. Sealant suppliers offer and recommend many sealants with varying compounds for IG assembly; spacer-bar systems span a wide variety of designs and materials. Along with these varying material choices, many of these component manufacturers continue to change many of the raw material inputs in their products as they develop low-cost alternatives, address specific customer requests, etc.

Each set of IG design, material and process alternatives creates unique variances. Assuring that the variances are reduced to a minimum increases the chance of producing acceptable, durable product. As part of the ongoing research, the team was invited to several window and door manufacturers, IG manufacturers and sealant manufacturers. Focus of these activities included investigating quality and specification processes intended to define, communicate and validate IG design and processing. Creating and implementing a quality assurance policy and procedure requires a set of metrics to be developed as the standard or goal of each manufacturing sub-process. This assures that all incoming material meets requirements through to the shipping of the final product. This set of metrics is the product specification, the recipe for an IG unit. IG specifications will be discussed in the next section, currently it is assumed that each IG manufacturing process has a recipe (specification) which includes the incoming materials; procedures for receipt, handling, and preparation of materials; procedures for mixing (assembling) materials, etc. The required and expected outcomes will then be well defined and based on customer expectations.

Based on the invited investigation which included observation, discussion, document and process review of the IG assembly operation, the following suggestions are made that can reduce IG failure rates and provide for continuing improvements.

Require material certifications, testing or acceptable documentation according to the materials specifications on all incoming raw materials to insure compliance to the IG engineering specifications.

As discussed above, the outcome of the IG design and engineering process produced the specifications describing the material properties, geometries, etc. necessary for the IG application. These specifications also include the acceptable variance of each of those properties. If the compiled list of material properties presented above is used for reference, keep in mind that:

1) The list includes properties which are not commonly found in published material specification sheets nor listed in common certification sheets.

2) The list was developed around the current set of assumptions tied to the program development. In consideration of IG durability, some properties may not be of consequence to long term durability and additional properties may be added based on their consequence to long term durability. For example, the current materials database recognizes the gas permeation rate changes due to the temperature of the material. At this time the program assumes there is no permeation rate change of consequence when the material is stressed, with resulting strain in a continuing cyclic manner. This assumption is under considerable review at this time.

3) Many of the material suppliers do not and are not required to measure these properties. Other raw material components such as spacer bars, corner keys, glass, etc. must meet a similar specification and should arrive with a material certification (confirmation) document assuring product acceptability and conformance.

In addition, agreements should be reached with each supplier assuring notification of <u>any</u> change in the incoming material processing. These changes would include requests for a temporary deviation of incoming materials. Working with the supplier, the changes can then be evaluated against the design and engineering specifications to ensure acceptability.

Follow all suppler recommendations for material handling, storage, etc.

Sealant, desiccants and other materials used in IG manufacturing often are delivered with detailed recommendations for handling and storage, even if for a relatively short period of time. This is due to the possibility of contamination. This could be surface or chemical contamination. These recommendations should be followed and become part of the work instructions associated with the manufacturing processes involved. Contamination can change the expected performance of the material in the short and long term thus causing immediate process challenges and premature product failures.

Extend the supplier recommendations for handling and storage to all remaining processing.

Recognize the intent or have the supplier explain the necessity and reasoning for the material handling recommendations. This will provide a clear understanding of how and what can affect the material in properties. Then, extend that thinking to all remaining processes. For example:

It is normally recommended that desiccant materials and adhesives be maintained in a sealed environment with no exposure to air. These materials become contaminated quickly with moisture and their performance will be negatively affected with premature exposure. Many of the manufacturing operations that were audited were designed with process hold times for spacer assembles waiting to be applied to the glass lites. Thus, desiccants and primary spacer materials that had been protected in sealed containers before application were exposed for varying periods of time in dusty and humid conditions as they waited for final assembly. Minimum exposure after desiccant application will insure a better performing IG over time. One solution would be to cut these hold times to a minimum or design the process for immediate assembly after desiccant and sealant application.

Cleaning recommendations are prevalent in the IG manufacturing processes.

As described above, contamination of surfaces must be addressed. Components should be assembled immediately after cleaning. Dust and other airborne contaminates can contaminate the material interfaces and reduce the expected performance of those interfaces. In addition, material handling of components after cleaning must be designed not to re-contaminate the surfaces; supporting the common recommendation of wearing the right gloves during the assembly process. Wearing no gloves will leave dirt and oils on the surfaces and some gloves (cotton) will leave the surface in a more contaminated condition as cotton fibers commonly are distributed on the surfaces.

Identify points in the processes to validate, control and improve the processing.

As described in the design and engineering specifications, each of the process steps involved in the manufacturing of IG units has an expected outcome described with an acceptable variance. The outcome of each process can be validated relative to its acceptable variance. A variety of efficient and effective quality tools and technologies can be implemented in the process to validate the outcome of one or more processes. These tools range from the simplicity of inspection with trained operator observation to implementation of sophisticated electronic equipment. A process for capturing the inspection data should be designed and implemented. The information can then be used to monitor the process in real time and make adjustments if necessary to assure the process step remains in compliance; controlling the process. In addition, the information can be used to evaluate the process over a longer period of time to support a number of design, material, process and cost opportunities.

Develop and implement an operator training process.

Along with common training requirements such as work procedures, machine operation, safety, etc. the items listed above are obvious candidates to be included in a training discussion. In addition, benefits can be gained in discussing the fundamental expectations of an IG unit. For example, a training program should include discussion addressing necessary IG product characteristics such as what IG units are designed to do (insulate, block and trap energy) and how they do it (sealed volume, thus it can have no holes, glass coatings refract and reflect energy, etc.). Include the efficient design and engineering characteristics such as the specification and application of the seal material as it relates to the handling, work instructions and quality requirements.

Currently, many industrial organizations and companies in the IG supply chain use comprehensive quality assurance programs and recommendations to include application of materials, quality process and procedure recommendations, etc. This includes the Insulating Glass Manufacturers Alliance (IGMA), the American Architectural Manufacturers Association (AAMA), and the Glass Association of North America (GANA). These efforts are in recognition of the need for improved and continuing quality in IG manufacturing. The documents available through these organizations and supply chain partners will provide more detailed recommendations and examples that can be customized to the specific needs of a chosen IG design and process operation.

Consistent quality of materials and quality assembly of IG units will have the most immediate impact for improved IG durability. As referenced earlier, Appendix 4 presents data from several years of testing on several common IG designs and suggests an initial mortality (units that failed the initial leak test) rate of 6.7 %. This mortality rate was directly attributed to manufacturing quality issues. Although there are several areas of materials research and design considerations which are anticipated to advance IG durability, consistent material and assembly procedures can currently reduce failure rates.

4.4.6 Product Specifications and IG Durability

The proceeding discussions and recommendations assumed that IG units were being manufactured to a set of IG product specifications. These specifications present variances or acceptable distributions of each material, component, and process attribute that then sets the metrics for controlling the manufacturing process through disciplined quality procedures.

It is recommended that the product specifications be developed during the product design processes. Thus, understanding the induced stress, both static and dynamic, and engineering the system to response as desired to those stresses must be done at the IG design level. The stresses that an IG experiences throughout its expected service life are notably transferred to a mounting system, a sash frame, window frame, door frame etc. These mounting systems also must be considered, pushing the need for specifications to be developed in collaboration with or distributed by window and door manufacturers and so on. Creating a specification for a durable IG with a 20 year service life requires the designer understand the IG as it relates to the building envelope and its environment, all customer (architect, builder, fenestration manufacturer) expectations and the supply chain expectations. Each of these can be considered to impart or impact a mechanical stress on the system creating the need to define requirements for the materials, processed components, sub-assembles, etc. Those requirements must be engineered into the product, creating the product specification.

In general, research activities to collect and document the IG design and engineering specifications produced very little. Due to intellectual property or trade secret concerns, this response is not totally unexpected. Many of the IG manufacturers have the ability to support the design and engineering processes in house while smaller manufacturers likely resort to outside contractors if the process is supported at all. Documentation addressing IG design and specification presented to the project generally took the form of material specification sheets distributed by the IG manufacturer's supply chain partners. The documents were assembled to represent the IG being manufactured with additional documents describing size and shape variation representing customer requirements. Most often, there were no documents which described the environmental application, material and other requirements or associated engineering calculations.

Many of these manufacturers assumed that additional engineering specifications responsibilities would be provided by their customers. While posing the same questions to the window manufacturers, many responded with a similar assumption that the builder or architect would provide them with additional specifications if required. From the builder and architect's perspective, the IG is one of a number of components in a window that is addressed while specifying the window unit itself. This specification is based on a specific building envelope application that is expected and specified to meet certain building code requirements. From their point of view, the IG specification occurs with the window design. The window subassemblies or component requirements are assumed to be engineered by the supplier to consistently meet all the specified code requirements. Yet, few if any building codes specify durability in a quantitative manner or service life for components of buildings. Thus, the IG product specification seems, at best to be distributed among a series of window supply chain participants.

Although many IG and window manufacturers have implemented and gained value from quality assurance activities, generally the quality assurance information is collected as required for a chosen certification program. Occasionally the data was demonstrated as a tool for process improvement and was rarely related to an engineering or product expectation. For many, it was not clear how the metrics they were using to define success on the manufacturing floor related to the requirements of a durable IG product. The validation for their success was passing the certification testing. The audit participants continually referred to the testing (e.g. ASTM E774 – E774, E2190, CEN EN 1279, ISO standards etc.) and the certification processes to support statements of quality in design, materials, process and durability.

This raises the questions around whether an IG specification designed, explicitly or implicitly, to meet all certification requirements correlates to IG durability expectations. If the specification considers only laboratory testing, the testing must be designed to impart expected stresses. Static, dynamic, or the equivalency of those stresses is expected to be incurred in the real world application over the life of the product. Further consideration will be given to this question in a later discussion.

Meeting code requirements, ASTM or CEN standards, and passing or periodically failing laboratory tests provides a great deal of value to the development process. This also provides a set of conditions which can be used to create and support an initial product/engineering specification. The stresses induced during the tests can be calculated and the product can be engineered to successfully respond, thus validating the design's capability to meet the certification requirements. The assembly of a performance based IG specification will consider these laboratory applied stresses along with consideration of the real environmental stresses that are expected to be applied to the IG over its service life. Appendix 9 presents a suggested list of expected elements to be covered in an IG product / engineering specification. The development of the performance based specification is one of the first steps in the processes. Whether completed at a window design level, IG design level, or an IG component and material level, performance based specification becomes a prescriptive recipe for successful IG assembly during manufacturing.

4.5 Stressors, Environmental Conditions and Severity Factor

Environmental conditions that affect an IG in a window installed on a building are influenced by weather conditions at the building site. Changing weather conditions affect the pressure differential across the sealant system and this causes stresses in the sealants and other materials in the IG assembly. Changing barometric pressure and wind conditions apply forces to the exterior of the IG. Internal forces are caused by the reaction of the internal gas to changes in temperature. Daily weather cycles also cause thermal expansion and contraction of the IG components, as well as varying vapor pressure stress across the sealant. These forces cause deflection of the glass lites and resultant stress in the sealant system.

Other weather cycles occur from warm and cold fronts moving across the building site. Seasonal weather changes bring the most variation in temperature. These weather changes result in a complex series of cycles that cause stress to the IG.

The cyclical nature of the environmental conditions is very evident in the data files. An expectation exists that IG units kept at constant conditions would have maximum durability. A reduced humidity environment reduces the vapor pressure stress across the sealant and would enhance durability. In general, the further the local environment varies from the ideal environment, the more severe the effect on reducing durability. The field data available during this project is not sufficient to determine the shape of this function.

The ideal gas law can be used to describe the internal IG conditions at an environmental temperature greater or lower than the initial IG build (final assembly) temperature. The calculated result is the pressure difference in pounds per square inch (psi) applied to the IG and caused by the exterior environment temperature and the calculated interior IG temperature. This pressure on an ideal IG with rigid walls is called the severity factor due to temperature, **sevt**, and is expressed in psi difference between the interior of the IG and the external environment. The difference in barometric pressure in the environment to the barometric pressure at which the IG was sealed during assembly is called the severity due to barometric pressure, **sevp**, and is expressed in psi difference between the interior of the IG and the external environment. These two values are summed to determine the total severity, **sevtota**l, which also is expressed as the difference between the interior pressure of the IG and the external environment. At times the **sevt** and **sevp** are additive and at other times they are opposing.

To clarify the conditions that an IG is exposed to, the weather conditions described above were used to calculate a "Severity Factor" caused by the environment. This numerical approach allows conditions in various locations to be compared. The Severity Factor in this Phase of the study was limited to temperature, barometric pressure, and humidity as they influence forces and stress in the IG. Future work is needed to factor in ultra violet (UV) energy, other solar radiation, and additional items which affect life of materials in an IG unit. The Severity Factor is the quantified value of the environmental induced forces that are applied to an IG at the given location and not the response of the IG to those forces.

The response of an IG is dependant upon glass thickness, glass coatings, spacer thickness, unit width, unit height, sealant type, spacer type, and other items. By separating the applied conditions from the response characteristics, a clearer picture of the IG conditions can be found. Each variation in specific IG construction can then be tested to the Severity Factor conditions, and the results compared to help determine IG durability.

The approach used was to first examine the stresses that would be placed on a sealed rigid chamber with the same dimensions as a typical IG unit. Temperature effects were calculated using the ideal gas laws. Barometric pressure changes result in direct pressure differentials across the rigid chamber boundaries. The computer program utilized data from the hourly records of 262 weather stations in the United States for the years of 1990 to 1995 to calculate a Severity Factor that would simulate environmental conditions applied to IG units.

A study of the Severity Factor using weather data for the US shows significant variations across the country.

The program starts with an assumed temperature, the barometric pressure, and the altitude that the chamber (or IG) is sealed. All of these values can be varied and the analysis rerun. For the analysis run, average IG temperature was assumed to be a function of the difference in a typical building interior temperature and the outdoor temperature. The data enclosed with this report gives the severity data based on building the IG at 70 F, 1013 mbars pressure (sea level at 14.7 PSI atmospheric pressure). Average IG temperature is the average of indoor and outdoor temperatures with a 15% bias for outdoor wind conditions. The calculated severity data is expressed in PSI applied to the sealed IG unit.

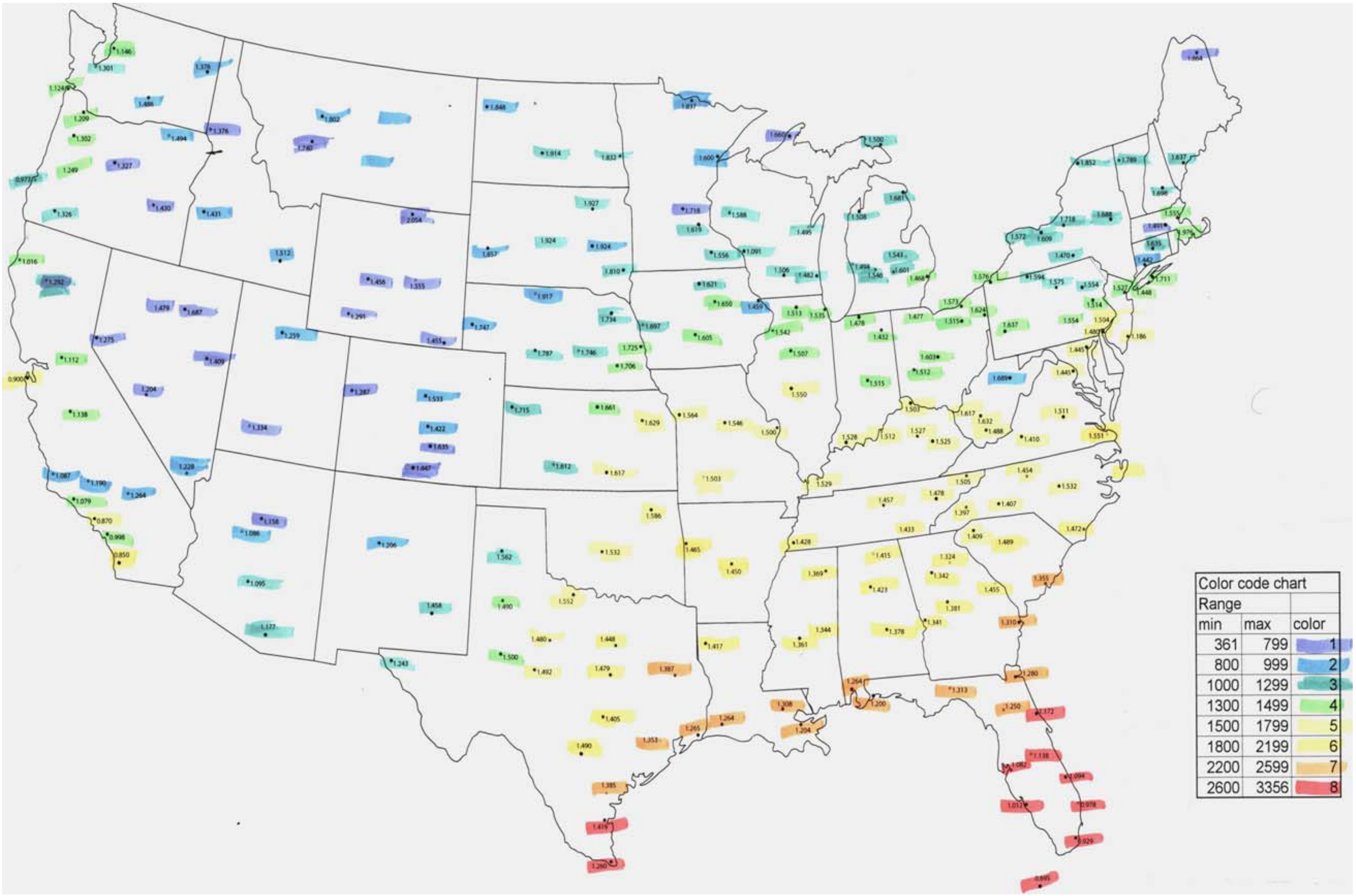
The response of an individual IG is dependent on the width and height of the unit as well as glass thickness and airspace thickness. Due to deflection of the glass lites, the interior pressure differential of an IG is less than the Severity Factor calculation. The deflection of the glass lites causes a peel type stress in the sealant system with actual localized stresses difficult to calculate. The Severity Factors calculated can be easily applied to an IG placed in a pressure chamber where the actual response of the individual IG can be measured. This separation of severity conditions from IG response conditions gives a clear view of the differences in IG stress exposure with changes in geographical locations. A plot of severity values for the US is given in a Postscript map file. Summaries of the data as well as the total data calculations are given in Excel files on the CD enclosed with this report. The resulting map presentation, Figure 4.5.1, of severity factors shows the wide distribution across the U.S.

Quantifying Environmental Stress

Figure 4.5.1 **Pressure Severity Map**

The severity calculations were expanded to include humidity conditions. Each hour of weather data was checked for the partial pressure of water vapor in the atmosphere at the IG location. As the temperature and humidity change, throughout each day, the partial pressure water vapor stresses change. This water vapor partial pressure exerts a stress on the sealants which drives moisture permeation through the sealant. The severity output files ".TX2" contain the hourly data on water vapor pressure. For each hour of humidity exposure, the water vapor partial pressure was summed into a term "psi-hrs" which expresses the cumulative effect of humidity exposure. Files ".TX3" and ".TX5" contain this total cumulative humidity vapor pressure data.

Figure 4.5.2 presents the Vapor Pressure Severity for the U.S., again, note the large variation across the country.



Color code chart		
Range		
min	max	color
361	799	1
800	999	2
1000	1299	3
1300	1499	4
1500	1799	5
1800	2199	6
2200	2599	7
2600	3356	8

Quantifying Environmental Stress

Figure 4.5.2 **Vapor Pressure Severity Map**

Included in the files on the disk is a data file for a very tropical climate on Barro Colorado Island in Panama. Higher total cumulative vapor pressure will increase moisture permeation through the sealant and reduce IG life. A properly desiccated IG with an internal dew point below -40 F has an internal partial pressure of water vapor below 0.003 psi (Ref.: File #11).

Figures 4.5.3 through 4.5.6 present the severity pressures from barometric and temperature data for the times and locations noted. In addition each contains the total severity from the addition of temperature and barometric severity pressures. While a chart is not shown for Barro Colorado, its inclusion would show the effects of extreme relative humidity.

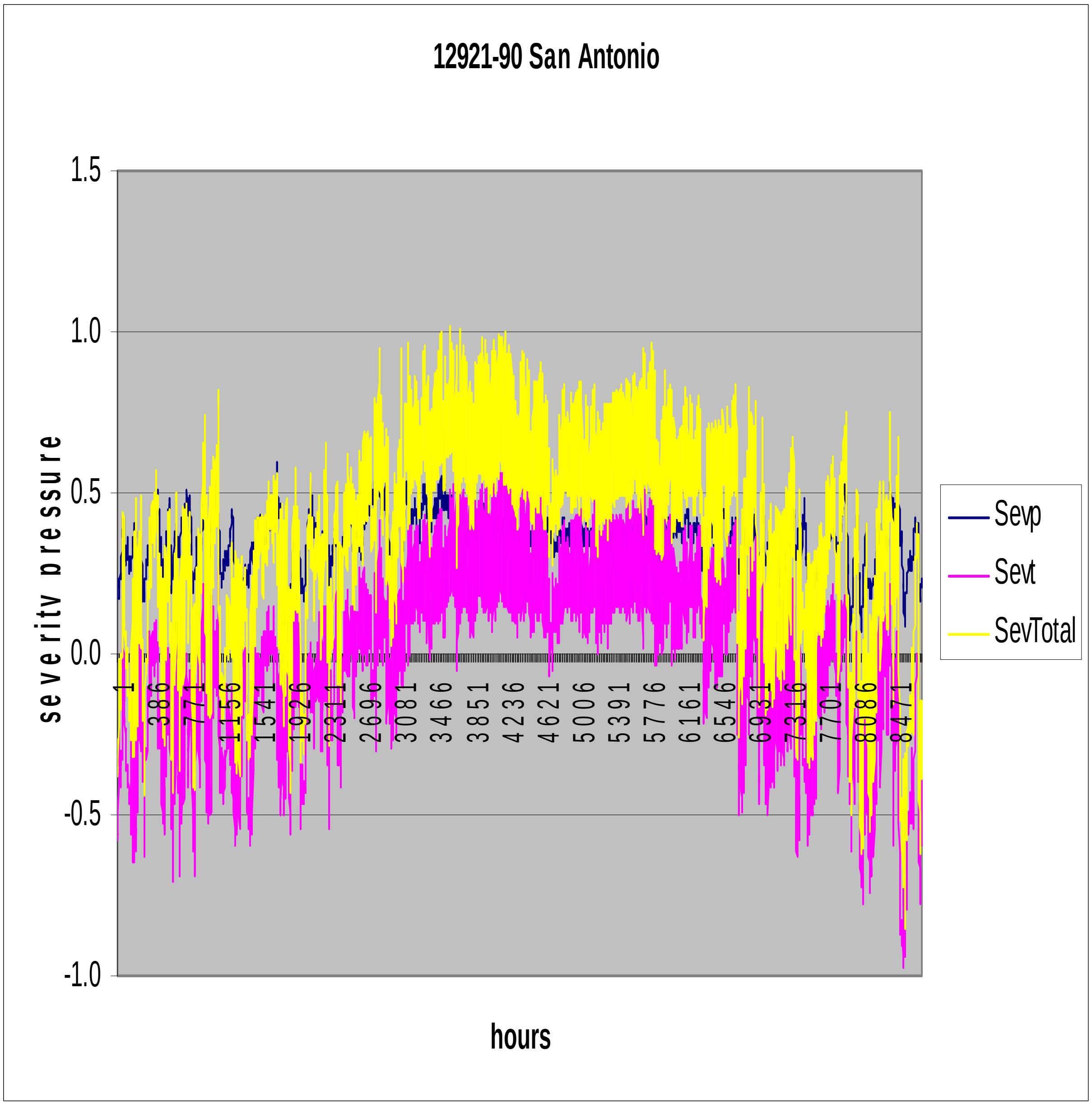


Figure 4.5.3 Graph of the severity pressures from temperature and barometric pressure for the year 1990 for San Antonio, Texas. Total severity pressure is also shown.

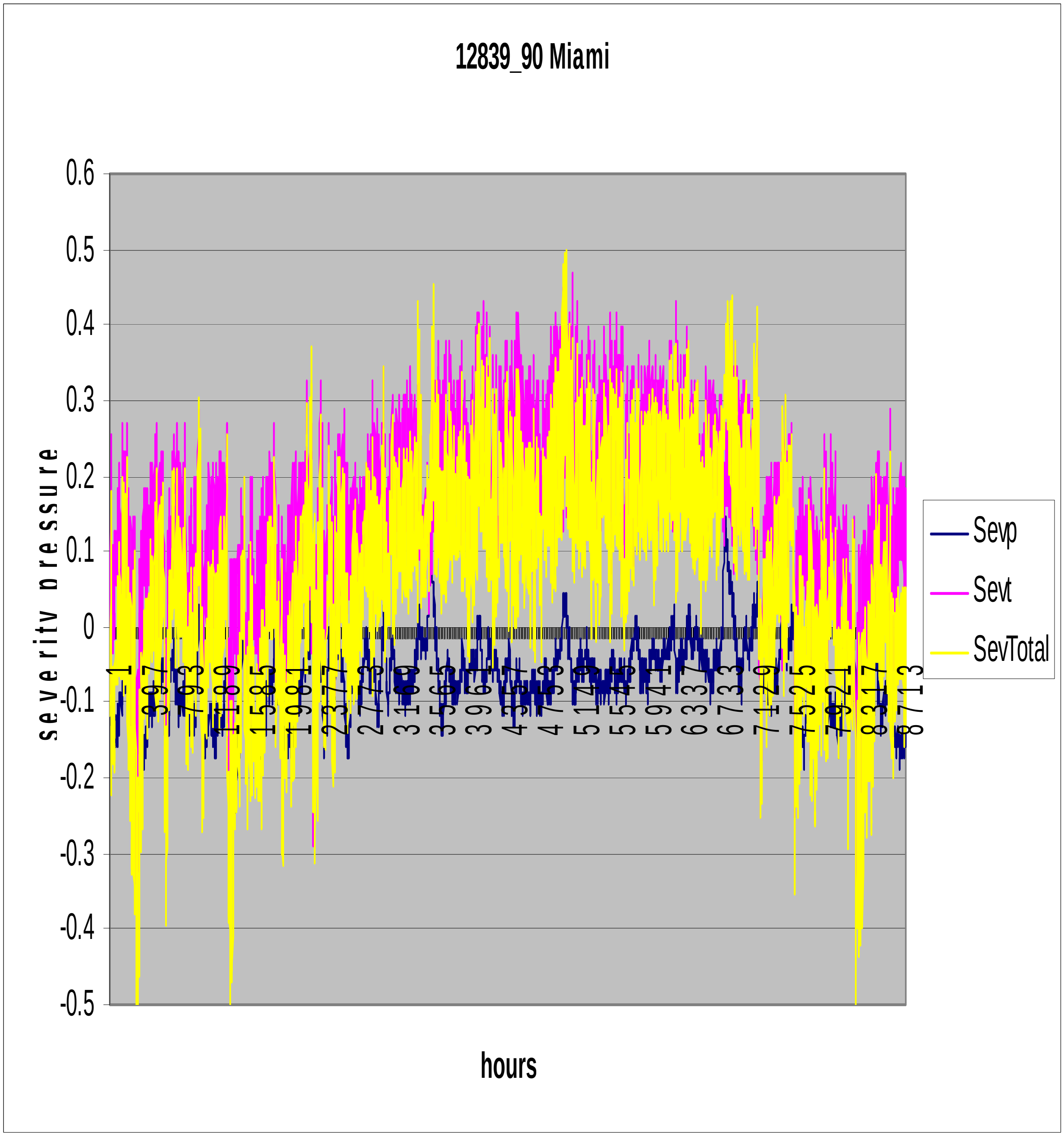


Figure 4.5.4 Graph of the severity pressures from temperature and barometric pressure for the year 1990 for Miami, Florida. Total severity pressure is also shown.

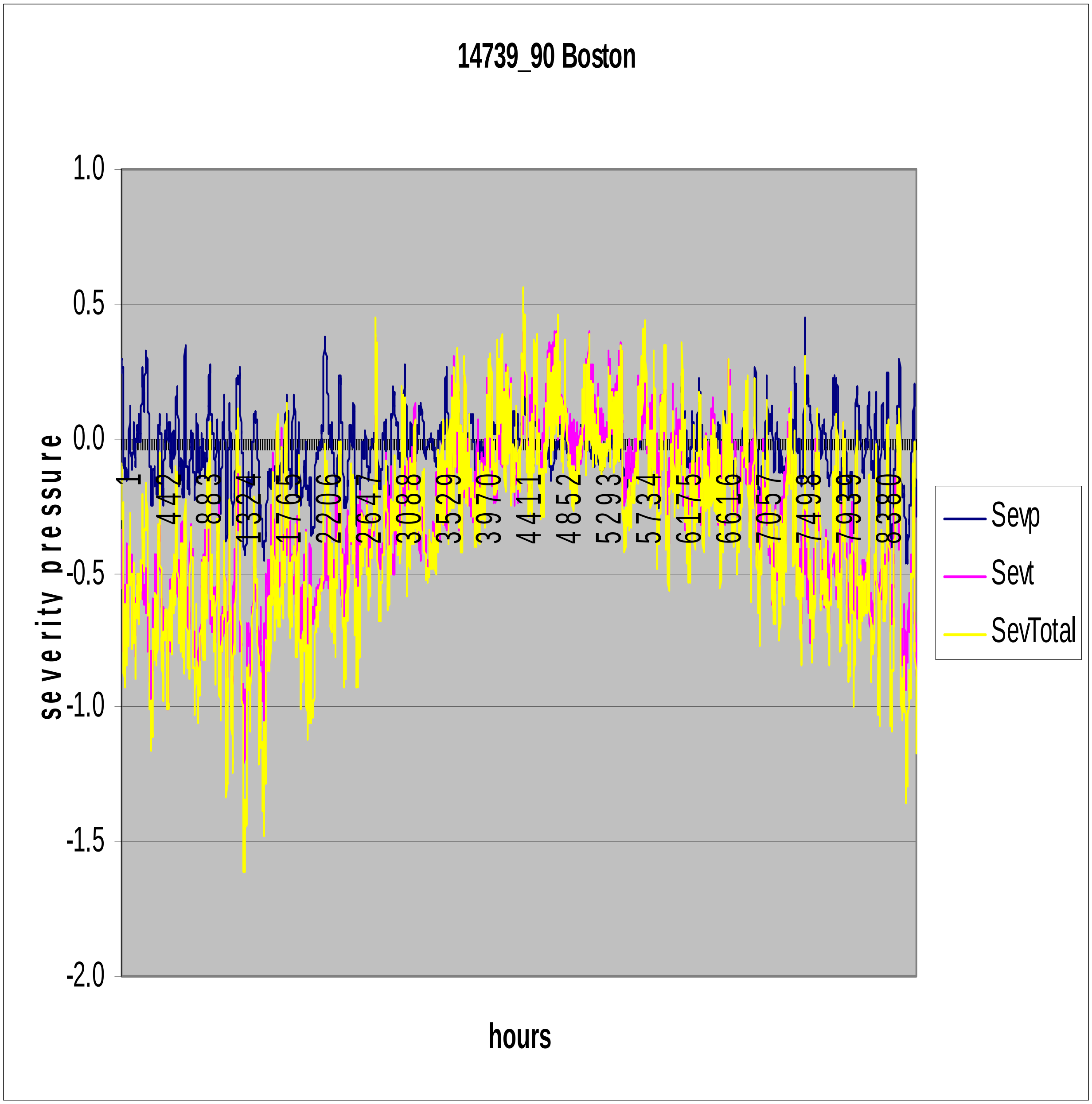


Figure 4.5.5 Graph of the severity pressures from temperature and barometric pressure for the year 1990 for Boston, Massachusetts. Total severity pressure is also shown.

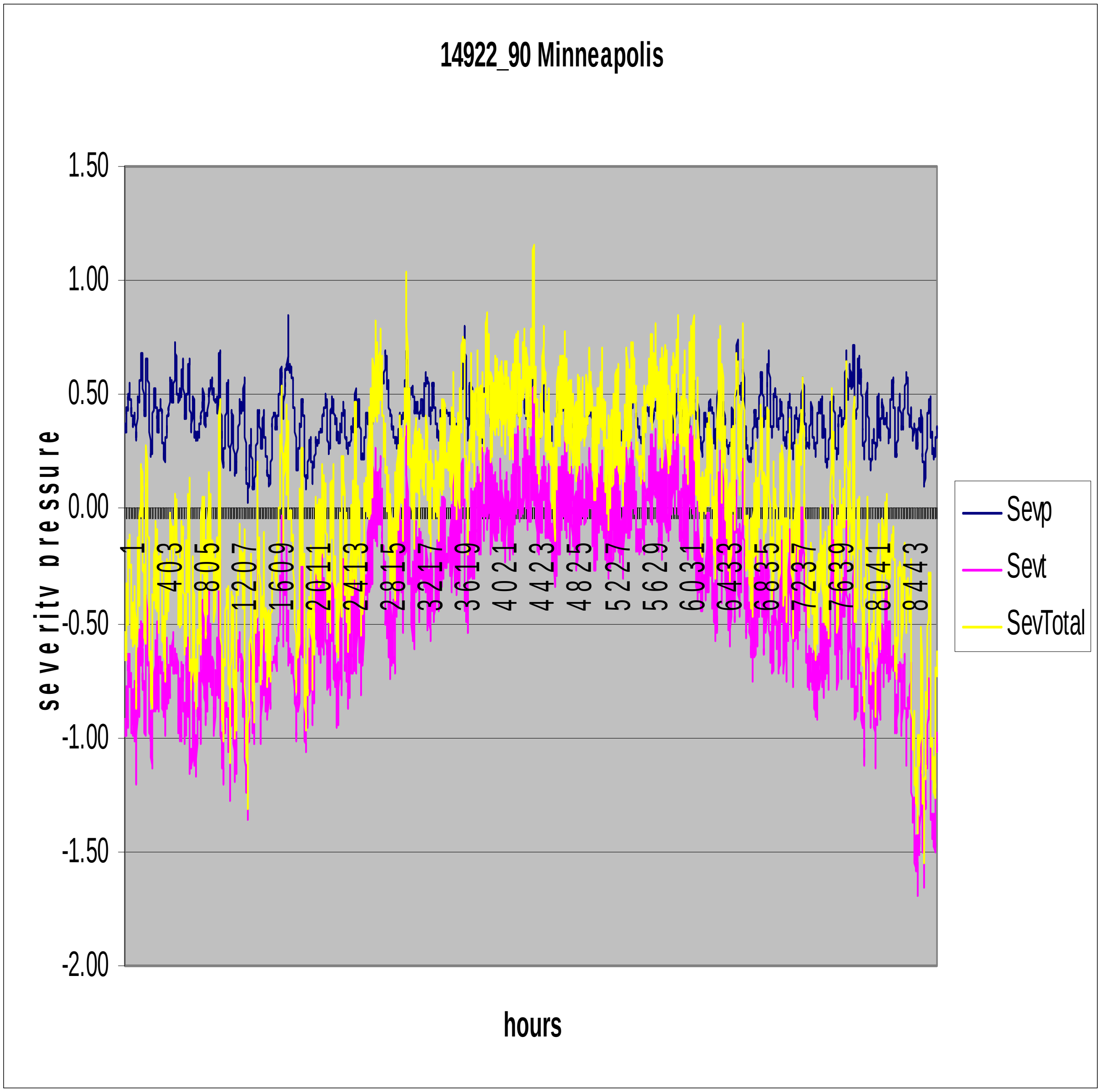


Figure 4.5.6 Graph of the severity pressures from temperature and barometric pressure for the year 1990 for Minneapolis, Minnesota. Total severity pressure is also shown.

There is a marked variation in severity conditions for the same weather station location for various years. Some years have more severe conditions than other years. While it is not possible to accurately predict future weather conditions, examining the data for a period of past years gives an ability to see the past effect of IG exposure. Sufficient data on IG failures is not available to correlate specific IG failures with specific weather patterns.

4.5.1. Format (TMY2)

Other window and IG reports have used the concept of a Typical Meteorological Year to show environmental conditions for different locations. Repeating the severity analysis runs on TMY and TMY2 files show less severe IG exposure conditions than are found using actual chronological weather conditions. The TMY and TMY2 files were developed for use with energy estimates and to simplify calculations. In the TMY2 format, each month is selected as most average over a number of years. Months with extreme conditions (high or low) are not used. IG units actually see the extreme conditions at the site where they are installed. These maximum stress conditions may significantly reduce the service life of the units. Where an accurate life prediction for IG units is required, actual weather station data with more severe conditions will result in more accurate results. An Excel file "realtmy2.xls" gives the comparison of the 1990 to 1995 weather station severity calculations with the same severity calculations for TMY2 files.

4.5.2. Weather Data Sources

Weather data for US weather stations is available from NOAA for the years 1960 through 2003. The calculation methods used here can be applied to this entire range of data for a more comprehensive picture of IG severity conditions. The calculation methods can be used with weather files for other countries to give a comparison of environmental exposure conditions.

4.5.3 Using the Environmental Data, Our Assumptions

The environmental data discussed above is widely used in building envelope analysis. In general the amount of data is such that averages or typical (TMY2) sets of data are used. The data is available and its acquisition, measurement, etc. is well known and there is a high level of comfort in its use. In much of the IG analysis work, air temperatures, barometric pressures, wind speeds, etc. are used in known and accepted mathematical models to understand energy related phenomena. Thus, knowledge of the effects of the environmental conditions on the surface and bulk material temperatures is of interest. The direct measurement of these dynamic temperatures can be prohibitively expensive and time consuming, thus assumptions based on proven and experienced heat transfer, absorption, etc. are made to reduce the expense and needed time for direct measurement.

In general these assumptions provide solutions which are precise and accurate for the purposes intended. This is especially true with most common building materials. The designs that use these materials consider very well known, relatively minor changes in material properties due to temperature. On the other hand, the sealant materials used in IG designs can have significant property changes due to temperature as discussed earlier.

4.5.4 IG Unit Temperatures - Primary and Secondary Seals

The window assembly, including the IG unit seal system, is at the interface of the building and the outdoor environment. The seal temperatures are not only dependent on the temperatures surrounding the window but are strongly affected by incidental sunlight.

Properties of sealants are known to change with the material's temperature. Wolf[3] has shown that properties of sealants such as moisture permeability and Young's modulus have a strong dependence on temperature. In order to estimate the performance of sealants it is therefore important to know what temperatures a sealant is likely to experience during the life of the window.

Limited data have been published indicating the seal temperatures experienced by an IG unit. Feldmeier, et al[4], have reported on the temperatures at the edge of an insulated glass unit. Their paper provides a histogram of edge temperatures over the observation period, ranging from below 0°C to greater than 60°C. Garvin and Wilson[5] have published interim results of a five year study in which they monitored the temperature and humidity in the glazing cavity for a variety of windows. They report that daily temperature ranges could be up to 20°C on summer days.

Nyström and Backman[6] determined the amount of UV light that could reach the sealant is a function of distance from the sightline.

Cardinal IG[7] has conducted an experiment to determine the seal temperatures experienced by IG units installed in a residential environment. The 99% argon filled IG units were made using a box spacer with a dual seal construction (PIB/silicone). Multiple thermocouples were mounted in the PIB sealant on both sides (indoor/outdoor) of the spacer. Each corner of the IG unit was monitored (8 thermocouples) as well as the midpoint of each side (8 thermocouples). In addition, thermocouples were mounted in the air space and on glass surfaces 2 and 3, for a total of 19 thermocouples per IG unit. The IG units were put into sash and installed with a southern exposure in an occupied home near Saint Paul, MN. Additional thermocouples were used at the site to record the indoor and

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[3] Wolf, Andreas T. and Waters, Leslie J., Construction and Building materials, "Factors Governing the Life Expectancy of Dual-Sealed Insulating Glass Units", 1993, Volume 7 Number 2

[4] Feldmeier, F.; Heinrich, R.; Hepp, B.; Schmid, J.; Stiell, W., „Alterungverhalten von Mehrscheiben-Isolierglas," Fenster und Fassade, **85**, (1-2), 198X, 3-7

[5] Garvin, S. L. and Wilson, J, "Environmental conditions in window frames with double-glazing units," Construction and Building Materials, **12** (1998), 289-302.

[6] Nyström, B. and Backman, Report of the Lund Laboratory of Glass Control AB, 1979.

[7] Cardinal IG, Minneapolis, MN

outdoor temperatures near the windows. Temperature data were collected every five minutes and the study was carried out for 14 months.

Figure 4.5.7 is an example of the indoor and outdoor temperatures recorded on two consecutive days in March. The first day was cloudy and the outdoor temperature varied less than 4ºC during the day ranging from -2.1 to 1.4ºC. The second day was sunny giving a slightly larger range of temperatures during the day, from -4.1 to 8.6ºC. The daily minimum and maximum temperatures at the nearest weather station are -3.3ºC and 3.9ºC for March 18th and -2.8ºC and 0.6ºC for March 19th.

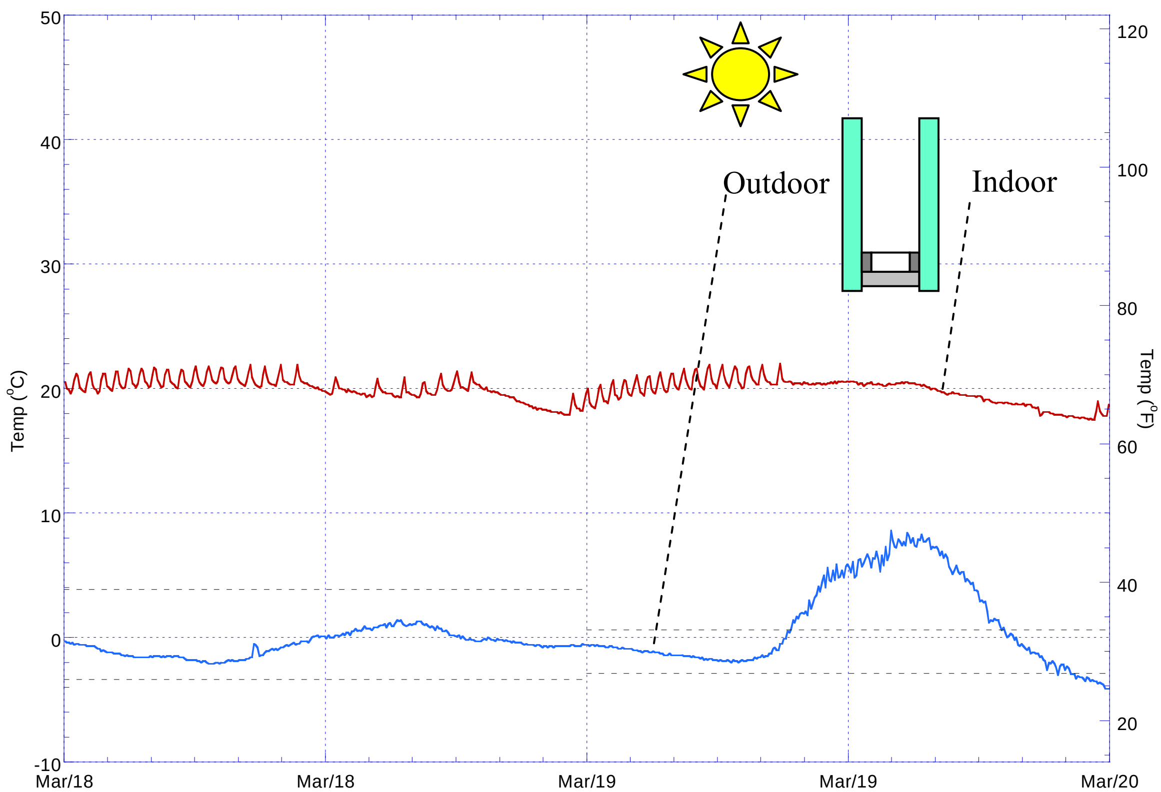


Figure 4.5.7 Interior and exterior temperatures near the casement window. Nearest weather station minimum and maximum are included for reference

The interior temperature data shows the influence of the furnace. During the night, the period of the furnace cycles is about 35 minutes and changes the air temperature near the

IG by about 1.5ºC. It is interesting to note that the furnace cycled several times during daylight hours of the cloudy day, while heating was not required on the sunny day. The interior temperature varied by 2ºC the first day and 2.5ºC the second day.

Figure 4.5.8 shows the temperatures of the glass lites and airspace during the same period. The temperature of the exterior glass lite (side #2) ranges about 6 ºC during the cloudy day while the interior glass lite (side #3) varies by about 3ºC. A modulation of the temperatures of the interior glass and of the air space due to the cycling of the furnace can be seen. That the temperature of the air space is closer to the temperature of the interior lite as compared to the temperature of the exterior lite is consistent with the presence of a low-emissivity coating ($\varepsilon = 0.4$) on the exterior glass lite (side #2). At night, the exterior glass is about 6ºC warmer than the outdoor temperature, increasing to about 10ºC during the overcast day. On the sunny day the change in glass temperature is more dramatic. The exterior glass temperature warms to 20ºC above the exterior temperature, reaching nearly 30ºC, while the interior glass lite and air space reach a temperature of 31ºC.

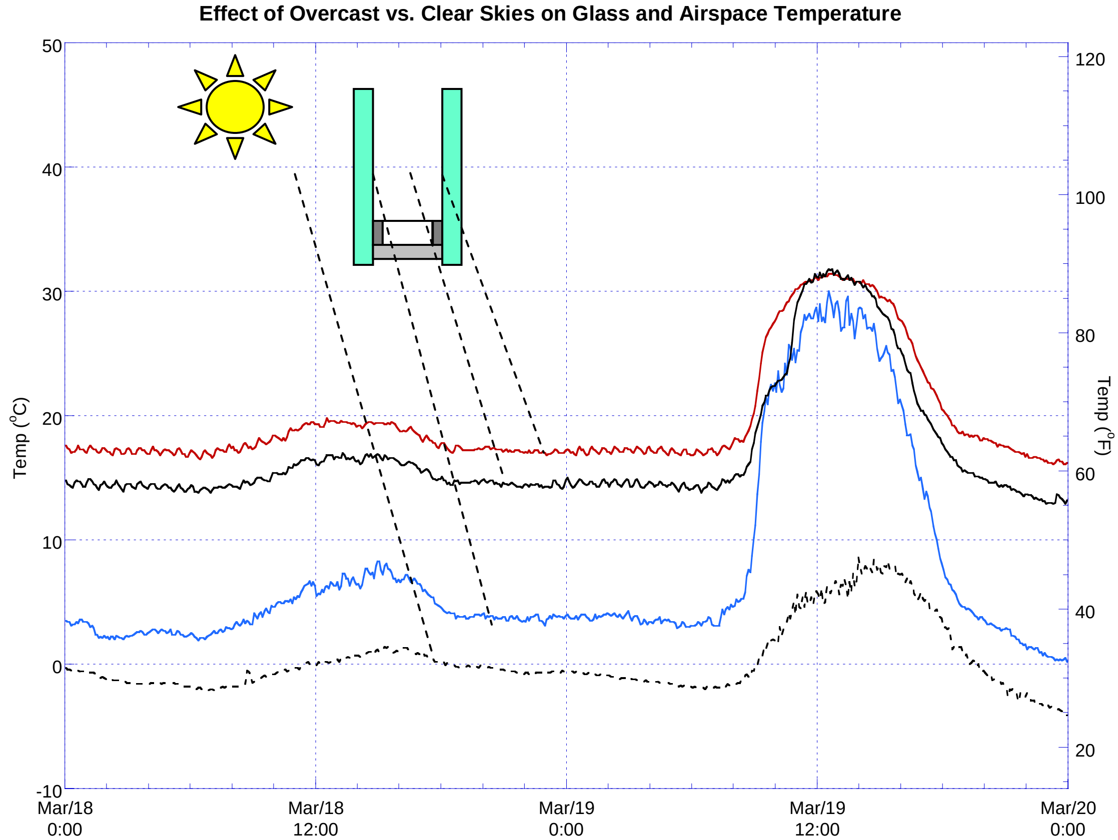


Figure 4.5.8 Glass and Air Space Temperature on a Cloudy and a Clear Day. Outdoor Temperature is included for reference.

The effect of the sun on the temperature of the PIB seal on the lower edge of the window is shown in Figure 4.5.9. On the overcast day, the inner and outer seal temperatures remain between the temperatures of the inner and outer lites of glass (Figure 4.5.8). On the sunny day, the seal temperature of the seals increases dramatically, reaching 50ºC. This is 20ºC warmer than the glass temperature, 30ºC warmer than the indoor temperature and over 40ºC warmer than the outdoor temperature.

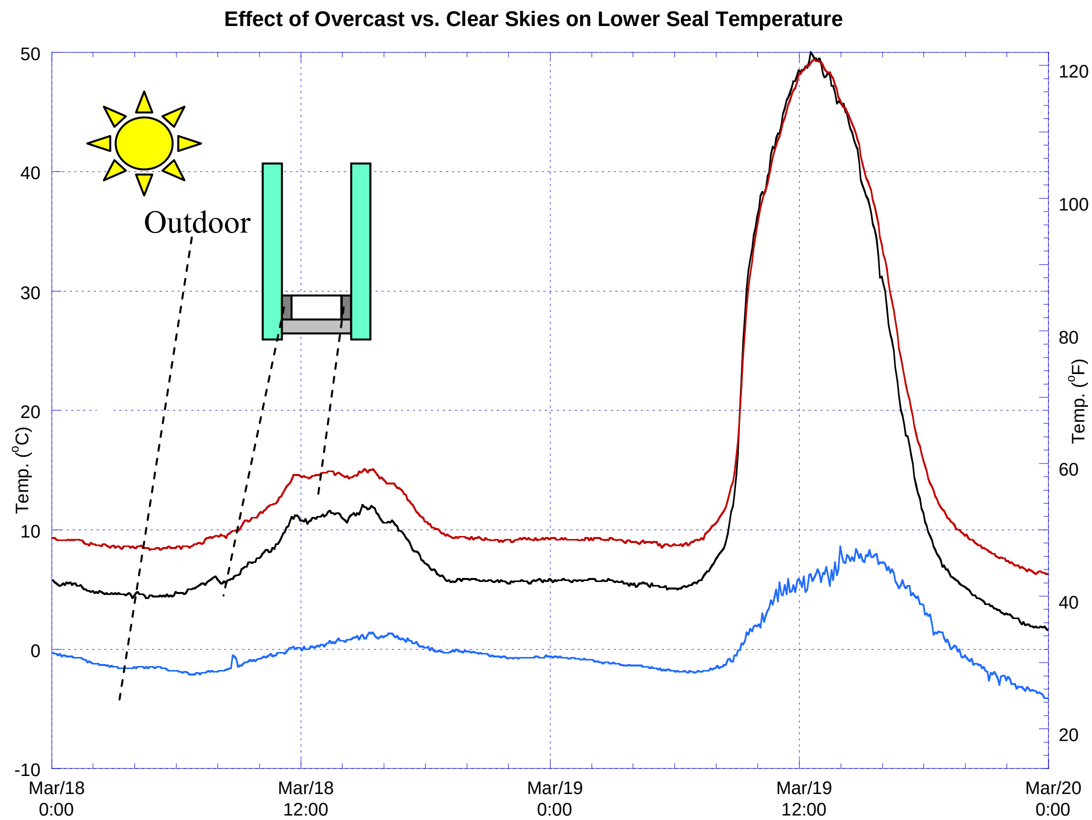


Figure 4.5.9 The Influence of Solar Radiation on PIB Seal Temperature at the IG unit Bottom Edge (brown sash). Outdoor temperature is added for reference.

The impact of direct beam solar radiation on seal temperatures around the window is seen in Figure 4.5.10. Prior to sunrise, the distribution of the seal temperatures are consistent with a top-to-bottom temperature gradient within the window[8]. The seal at the top of the window is the warmest, the seal temperature on the sides of the window are cooler, while the seal temperature on the bottom of the window is the coldest. The seal at the bottom of the window receives the most sun at the middle of the day, reaching 50ºC. At the top of the window, the sealant remains shaded by the sash throughout the day, reaching a peak temperature 28ºC, 20ºC cooler than the bottom seal.

[8] Carmody, J., Selkowitz, S. and Herschong, L. "Residential Windows: A guide to new technologies and energy performance," W.W. Norton & Company, New York, 1996.

Due to the orientation of the window on the house (southern exposure), the right side (as viewed from the interior) is exposed to the morning sun and is shaded by the window sash in the afternoon. As can be seen below, the seal temperature on the right side has the most rapid rise in the morning and its temperature peaks before noon. The left side of the window experiences the opposite effect, being shaded by the window sash in the morning and exposed to the sun in the afternoon, achieving its highest temperature about three hours after the right seal. We cannot determine at this point how much of the heating is due to adsorption of solar radiation by the sealant/glass within the glazing rebate or what other sources of shading (overhangs, setbacks, mulling strips, etc.) could be influencing the temperature profiles.

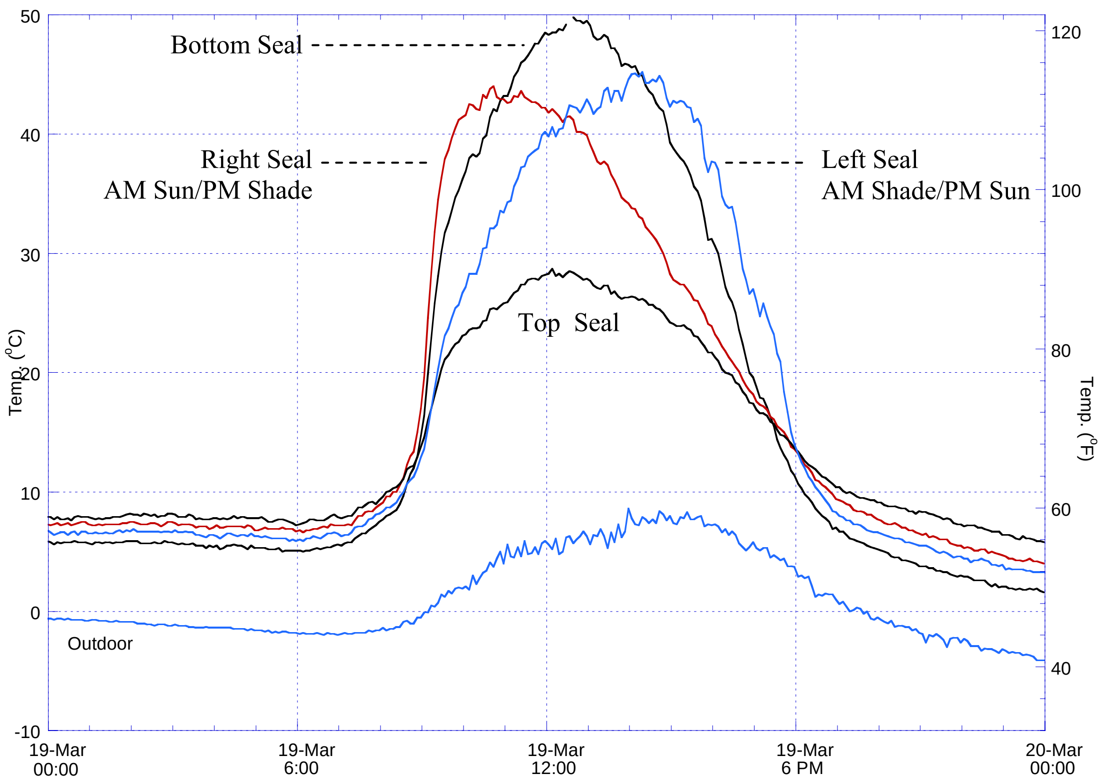


Figure 4.5.10 The Influence of Solar Radiation on Seal Temperature Exterior PIB Seal temperatures in the midpoint of each side

The temperature of the seals is also impacted by the color of the sash that surrounds it. Colors that absorb more of the solar spectrum are warmed more by the sun and transfer the heat to the seal. The bottom seal temperatures for an IG unit in white and brown sash are shown below in Figure 4.5.11. Overnight the seals have the same temperature. When in the sun, the seal temperature of the darker sash is 10ºC higher.

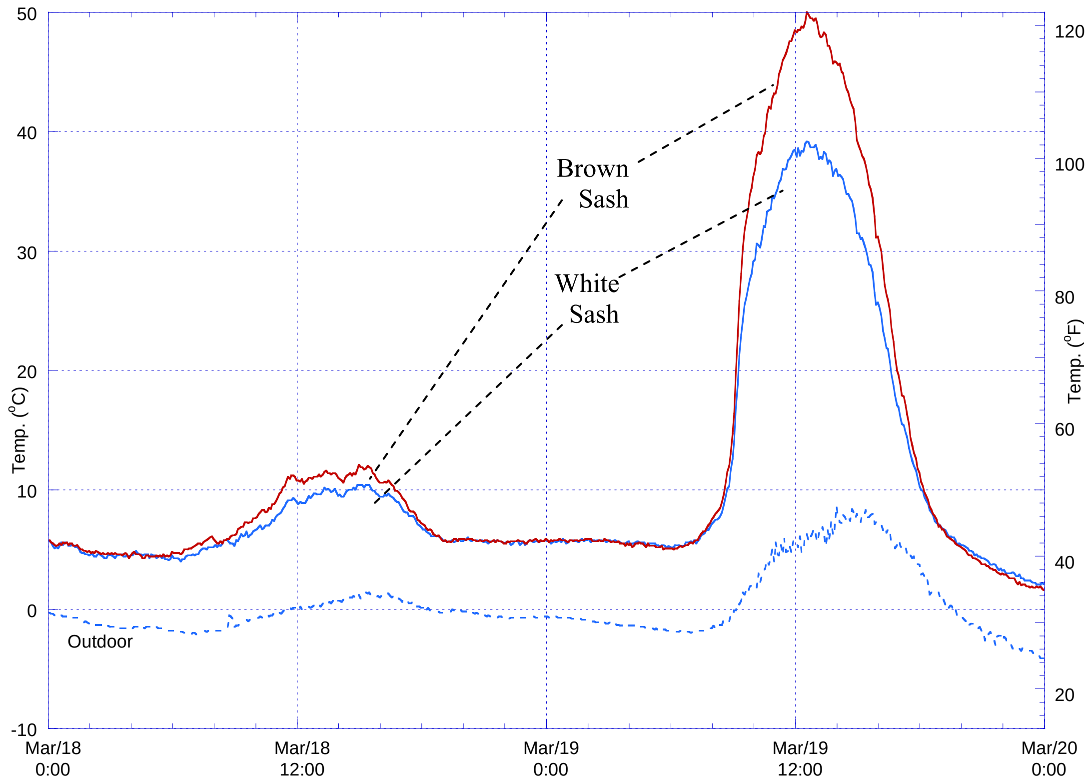


Figure 4.5.11 The Influence of Solar Radiation on Temperature of the exterior bottom PIB Seal temperatures for brown and white sash

As with the brown sash, the white sash seal temperatures around the window are affected by shading from the sash. The largest seal temperature differential on this day reaches about 15ºC, about 5ºC cooler than the temperature differential recorded for the brown sash.

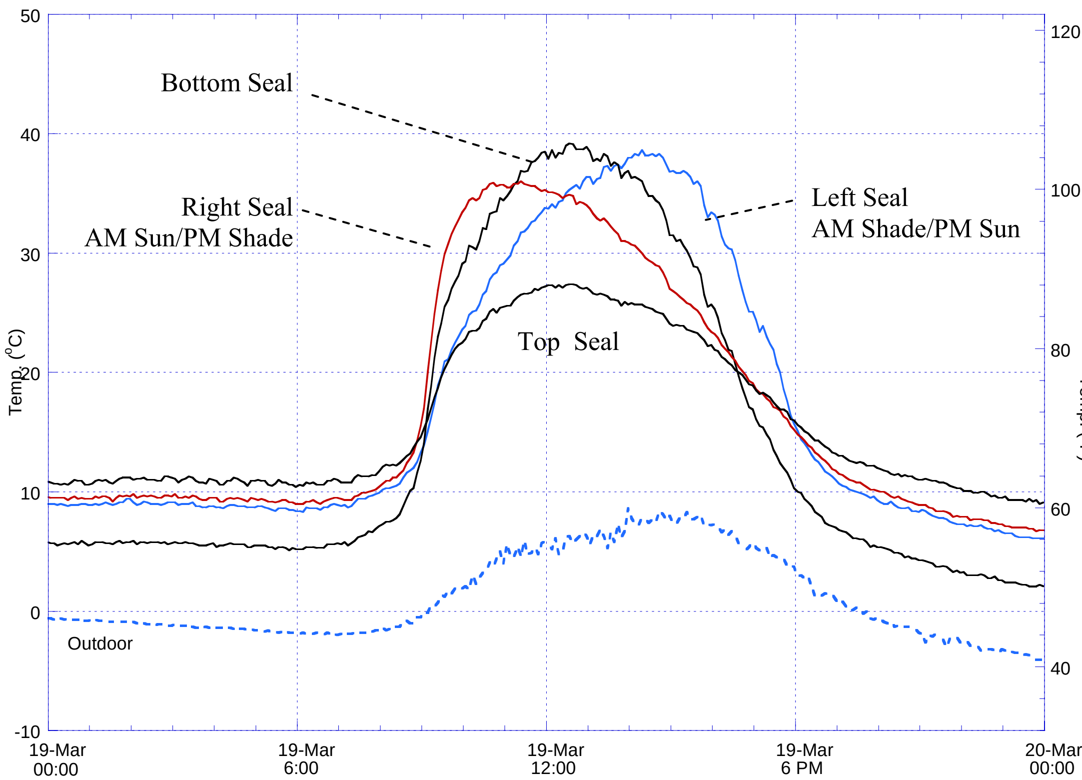


Figure 4.5.12 The Influence of Solar Radiation on Seal Temperature Exterior PIB Seal temperatures in the midpoint of each side – White Sash

Conclusion

The field data show that the temperatures experienced by the seal can be significantly higher than is indicated by the glass temperatures and that significant variation in temperature can exist in an IG unit at a given time. It is unclear how such temperature differences might impact the service life of an IG unit and current IG unit testing protocols do not subject the IG unit to such asymmetric stressors.

Accurate estimation of temperatures is important in estimating the service life of an IG unit because the permeation properties of the sealants depend on temperature and stresses that can be induced by thermal expansion of the IG unit components. The Durability Design

Tool has limitations in this regard. First, the seal temperatures are assumed to be equal to the glass temperatures which, as shown above, can easily lead to 20ºC temperature error on a sunny day. This will lead to errors in calculation of thermal expansions and permeation. The permeation limitation can be overcome by providing the Durability Design Tool with a file of seal temperature as a function of time to use in the simulation. An additional limitation is the simulation assumption that the temperature of the seal is uniform at any given time.

4.5.5 Seal - Humidity (absorption)

The severity calculations were expanded to include humidity conditions. Each hour of weather data was checked for the partial pressure of water vapor in the atmosphere at the IG location. The temperature and humidity change throughout each day; the partial pressure stress changes also. This water vapor partial pressure exerts a stress on the sealants which drives moisture permeation through the sealant. The severity output files **".TX2**" contain the hourly data on water vapor pressure. For each hour of humidity exposure, the water vapor partial pressure was summed into a term "psi-hrs" which then expresses the cumulative effect of humidity exposure. Files ".**TX3**" and **".TX5**" contain this total cumulative humidity vapor pressure data. On the disk is a data file for a very tropical climate on Barro Colorado Island in Panama. Higher total cumulative vapor pressure will increase moisture penetration through the sealant and reduce IG life.

4.6 Failure Metrics

As discussed in the previous section, the application of accurate temperatures will have an impact on understanding IG durability. In addition, as discussed below temperature is a factor in most of the identified failure metrics.

4.6.1 FMEA Target

IG unit failure is considered from the perspective of the consumer: if the IG unit would be perceived by the homeowner as not meeting the window's structural requirements and visual aesthetics, it is considered to have failed. These conditions include glass breakage and condensation within the IG unit. The fault tree diagrams developed using FMEA for a given IG unit design (see Phase I Report) were used to define which of the failure modes lead to the product failure. Such failure modes include the loss of adhesion between a sealant and the glass or poor moisture vapor permeation resistance of a sealant. A complete listing of the failure criteria that can be used in the simulation is given below.

4.6.2 Energy Efficiency

The energy performance of the IG unit during the simulation is followed by calculating its heat transfer coefficient. Although the heat transfer coefficient is calculated with the same method as the U-Factor used to determine the energy performance for NFRC and Energy Star®[9] certifications, an important distinction must be understood. The calculation of U-Factor used for the NFRC and Energy Star®[10] certifications is made using a static set of environmental conditions. For example, the NFRC[11] winter U-Factor calculation, specifies the outdoor temperature is -18°C, the indoor temperature is 21ºC, the outdoor wind speed is 5.5 m/s, the glass lites are always parallel and the contribution of solar radiation to heat transfer will be ignored. As part of the durability simulation, a calculation of the heat transfer coefficient is made using environmental conditions (temperature and wind speed) at that point in the simulation, thus the heat transfer coefficient at that point in the simulation is dependent on the temperature, which is continually changing. As with the NFRC U-factor, the solar contribution is not included in the heat transfer coefficient calculation in the durability simulation. Changes in the IG unit geometry (glass separation)

[9] Energy Star® is a registered trademark of the United States Environmental Protection Agency
[10] Energy Star® is a registered trademark of the United States Environmental Protection Agency
[11] NFRC 100-2004 "Procedure for Determining Fenestration Product U-Factors, National Fenestration Rating Council, Inc.2004 (http://www.nfrc.org)

are taken into account by the simulation in the calculation of the heat transfer coefficient. In general, an IG unit's heat transfer coefficient, as calculated by the simulation, will differ from the unit's U-Factor as determined using NFRC conditions due to differences in the environment (temperatures and wind speed) and deviations from a parallel glass geometry assumed for NFRC calculations.

Moisture condensation within the IG unit can be more than an aesthetic problem when low emissivity coatings are involved. If moisture condenses onto a low emissivity coating, the energy performance of the window will suffer. The emissivity of that surface changes from the emissivity of the coating (as low as 0.04) to the emissivity of the water film (0.95), significantly increasing the rate of radiant heat transfer. These changes or failures of the coatings are not considered in the current version of the durability tool.

Failure Criteria

Available for inclusion or exclusion in any specific simulation run.

General:

- Heat transfer coefficient exceeds the user set limit (calculation assumes no solar radiation)
- Desiccant water load exceeds the user set fraction of theoretical maximum

Condensation Related:

- Dew point in the gas space exceeds the user set limit
- Condensation on glass surface #1 (outdoor surface of outer glass lite)
- Condensation on glass surface #2 (gas-space surface of outer glass lite)
- Condensation on surface #3 (gas-space surface of inner glass lite)
- Condensation on surface #4 (indoor surface of inner glass lite)

Gas Loss from the IG:

- Gas loss exceeds the user set limit (10 gases possible)

Glass Lites:

- Stress of the outdoor glass lite exceeds limit
- Stress of the indoor glass lite exceeds limit
- Average distance between glass lites drops below the user set limit
- Deflection of the outdoor glass lite exceeds the user set limit
- Deflection of the indoor glass lite exceeds the user set limit
- Distance between glass lites at the center points drops below the user set limit

Inner Seal Failure:

- Effective cohesive stress of the inner seal exceeds the user set limit
- Tensile strain of the inner seal exceeds the user set limit
- Shear of the inner seal exceeds the user set limit
- Compressive strain of the inner seal exceeds the user set limit

Outer Seal:

- Effective cohesive stress of the outer seal exceeds limit
- Tensile strain of the outer seal exceeds limit
- Shear of the outer seal exceeds limit
- Compressive strain of the outer seal exceeds limit

Wet Seal:

- Tensile strain of the wet seal (outdoor) exceeds limit
- Tensile strain of the wet seal (indoor) exceeds limit
- Compressive strain of the wet seal (outdoor) exceeds limit
- Compressive strain of the wet seal (indoor) exceeds limit

Adhesive Stresses:

- Adhesive stress of the inner seal/glass interface exceeds the user set limit
- Adhesive stress of the inner seal/spacer interface exceeds the user set limit
- Adhesive stress of the outer seal/glass interface exceeds the user set limit
- Adhesive stress of the outer seal/spacer interface exceeds the user set limit

The failure criteria, designated above as "user set," are defined by the user using the GUI. The remaining failure criteria are determined by the data contained in the Materials Database.

4.7 Final Design Tool Development

With consideration for the preceding sections, the following will progressively analyze the inputs required in the current version of the durability tool. The continuing discussion explores the current tool while presenting relationships to existing analysis tools and future enhancement opportunities.

4.7.1 Graphical User Interface (GUI), Step by Step

This section discusses the design of the Graphical User Interface (GUI), which is used to control the simulation. With the GUI, the user can 'assemble' the IG unit to be tested, define the environmental conditions of the simulation, decide which of the 44 failure criteria will be evaluated, set the simulation parameters, launch the simulation and review the results of the test. The GUI is organized in a tree structure under which nodes and sub nodes are nested. The main nodes are (also shown in the left column in the Figure 4.7.1.1):

Case Name
IG unit Definition
Physical Models
Initial Conditions
Climate Data
Failure Criteria
Time Settings
Simulation Control

Every node in the simulation is associated with a data input window, which will be displayed in the gray box on the right when the node is selected. The GUI reviews the data tree to ensure that all data needed for a simulation are entered before a simulation can be run. The GUI alerts the user to nodes with missing data by shading the appropriate node in data tree red (see Figure 4.7.1.1).

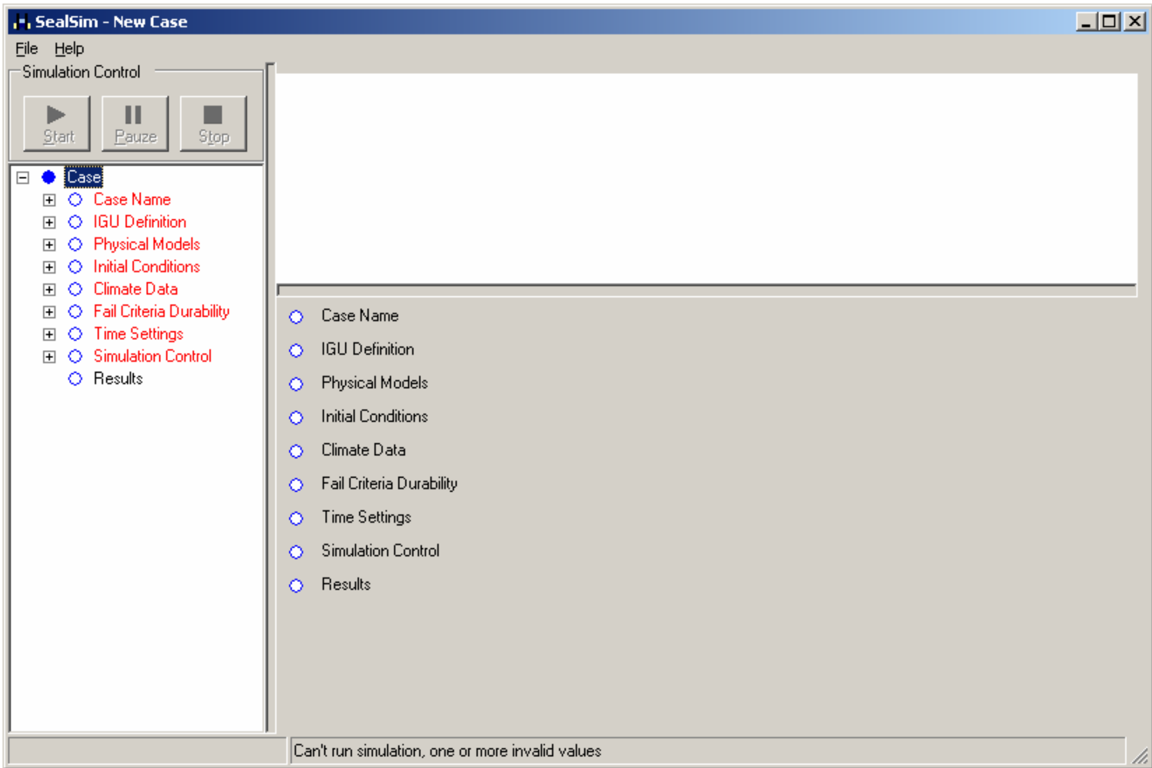


Figure 4.7.1.1 Initial screen for the SealSim GUI

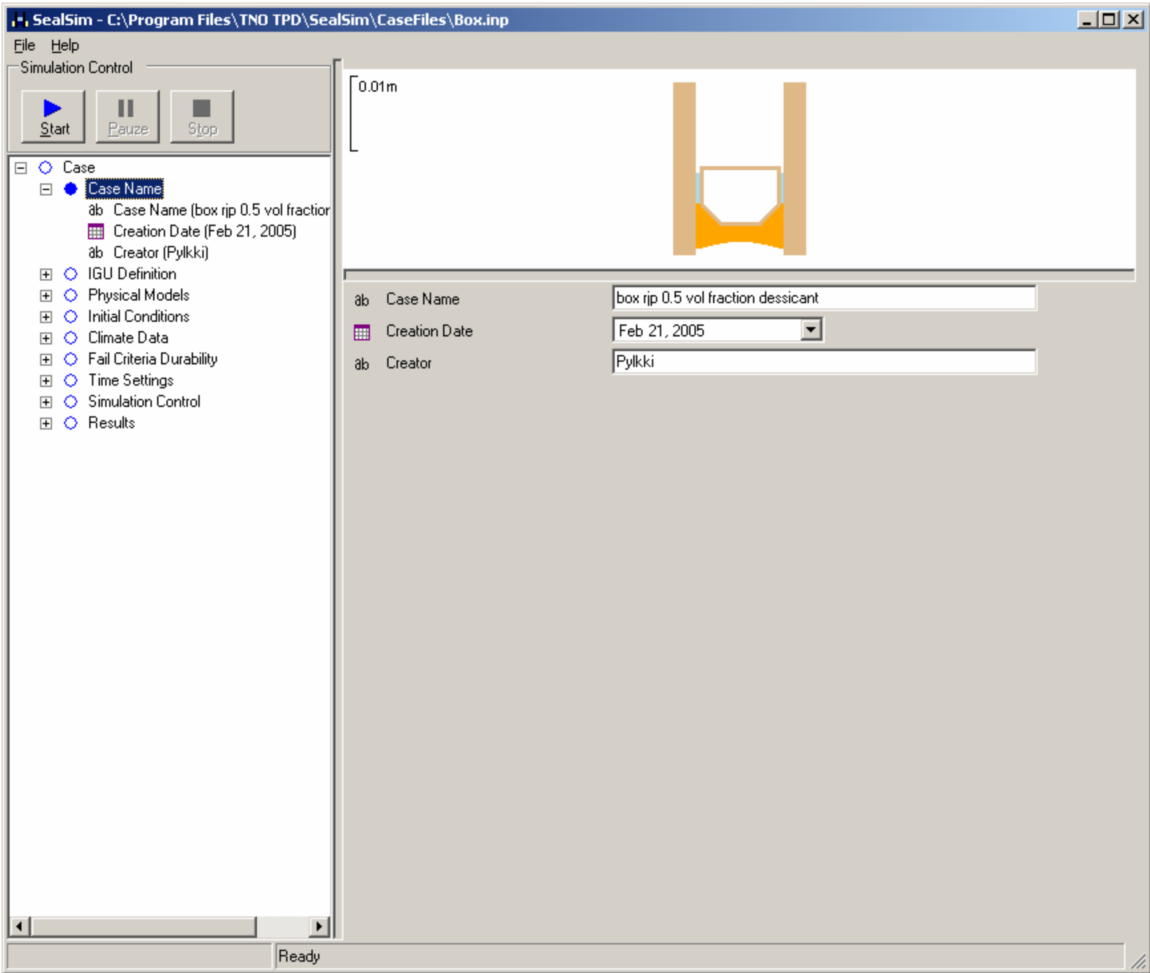


Figure 4.7.1.2 **Case Name input screen**

The Case Name (Figure 4.7.1.2) node is used to provide a name, the date and creator for the simulation. The name field can be used to provide a description of the simulation and is limited to 100 characters. The case name will be included in the simulations output file.

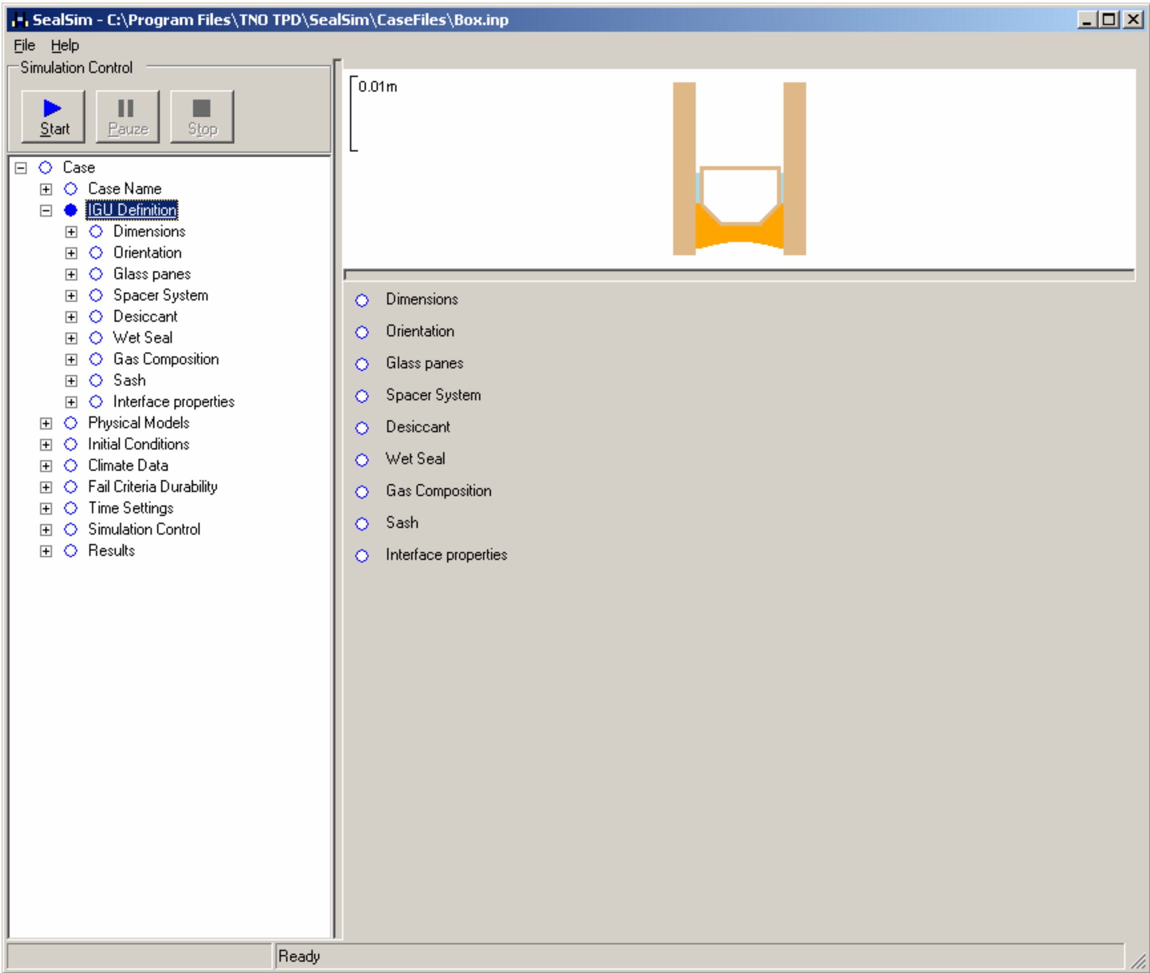


Figure 4.7.1.3 **IG unit definition screen**

The IG unit Definition node is used to construct the IG unit that will be simulated (Figure 4.7.1.3). Inputs in this node include glass dimension (Figure 4.7.1.4) and the installation orientation for the window (Figure 4.7.1.5) Orientation is included since the simulation takes into account the heating by the sun and wind loading for some model and material calculations.

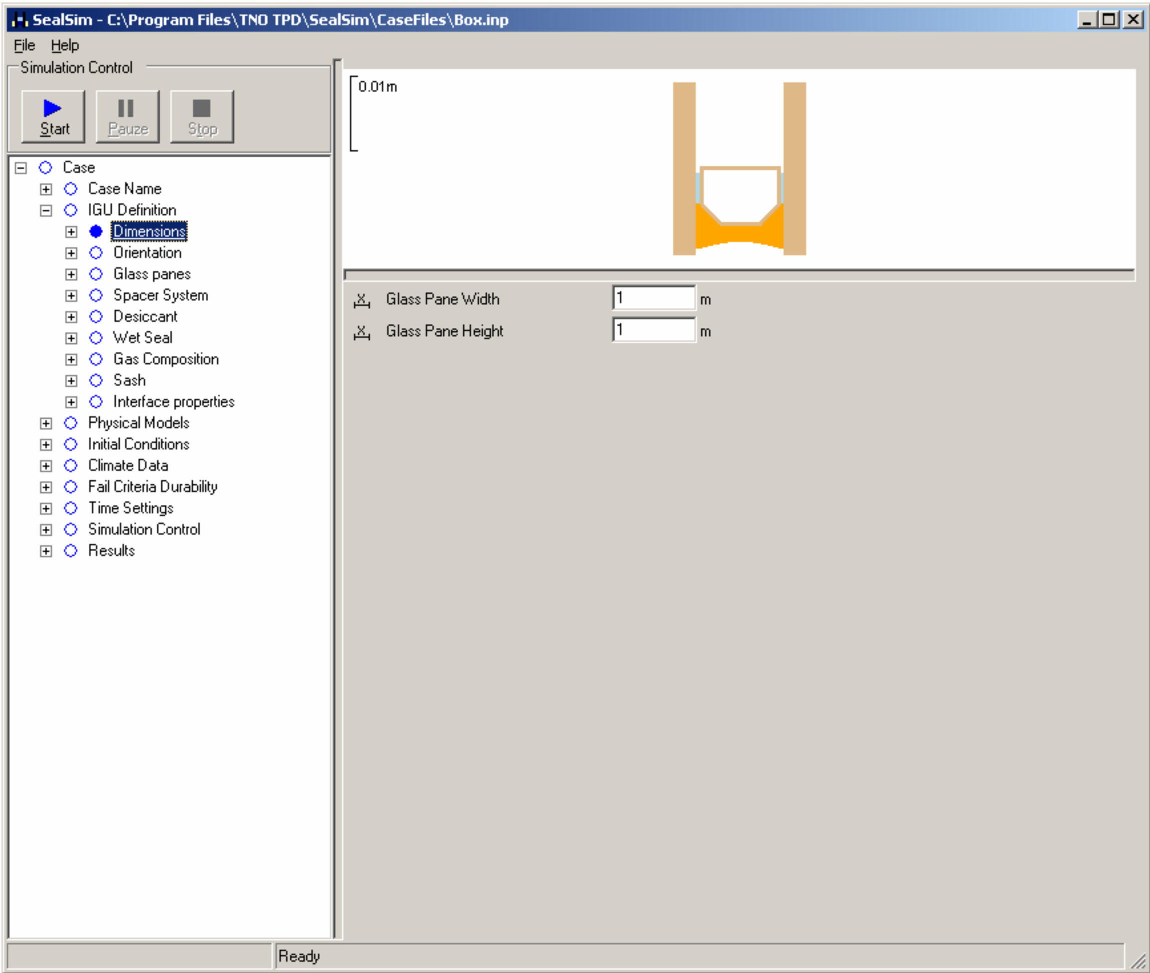


Figure 4.7.1.4 **IG unit Dimension input screen**

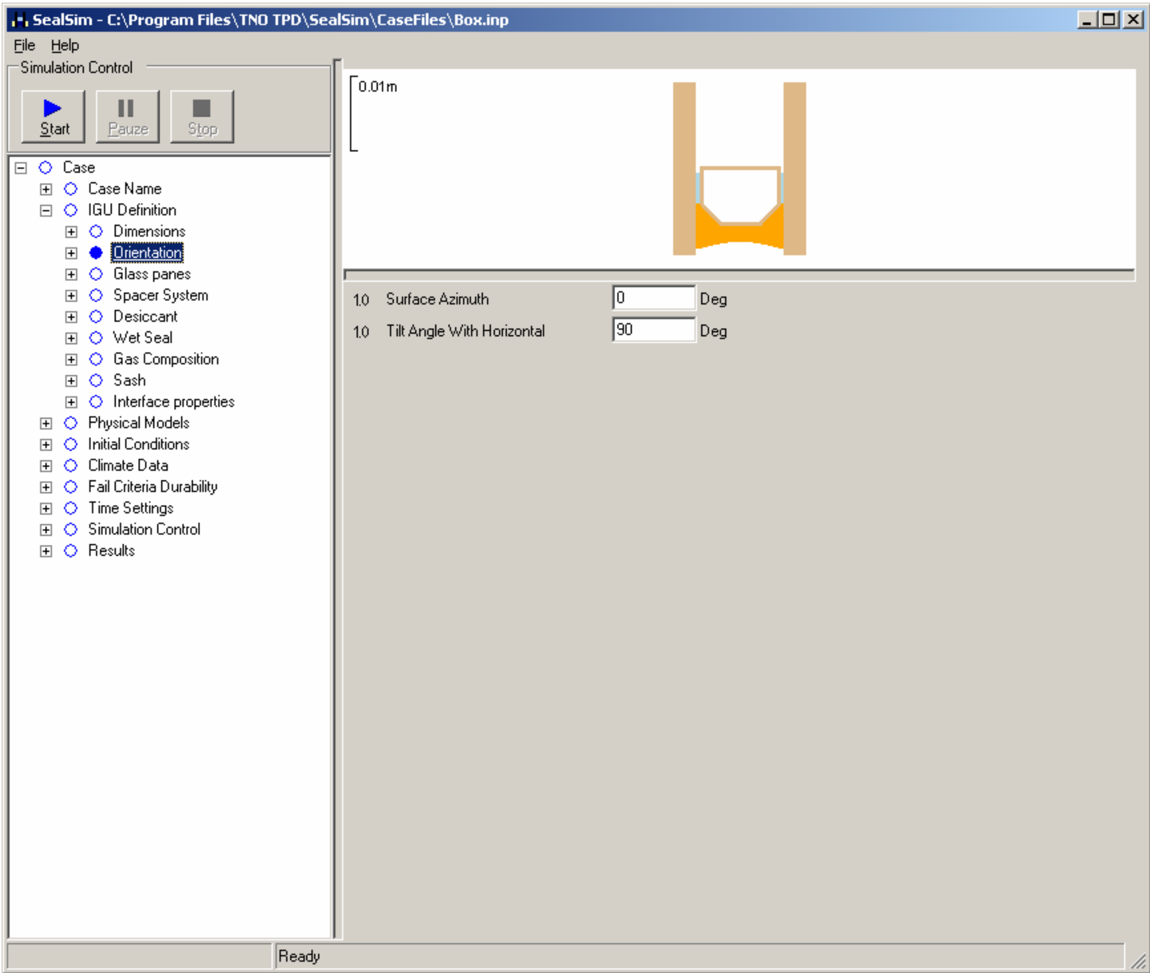


Figure 4.7.1.5 Orientation input screen

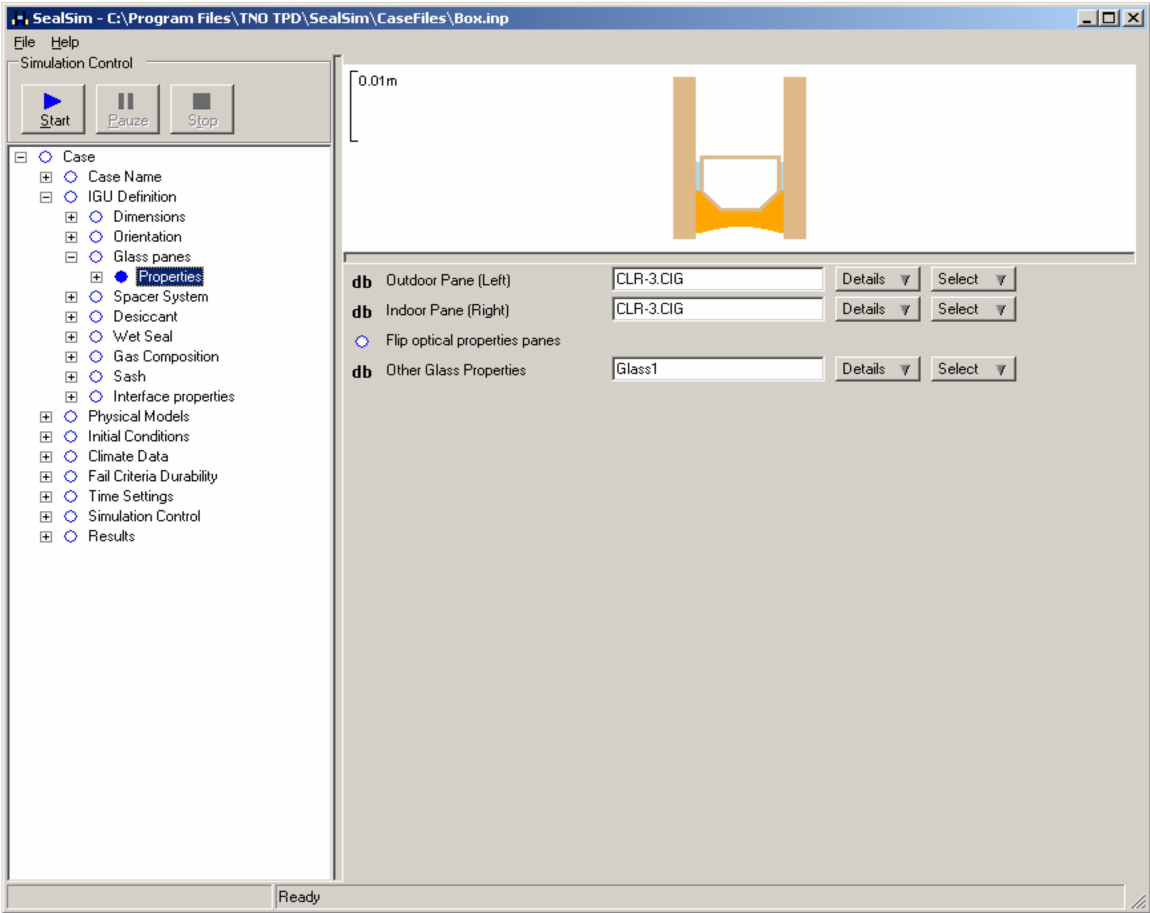


Figure 4.7.1.6 Glass lites/properties input screen

Details of the glass used for the IG unit are selected in the "Glass Panes – Properties" screen (Figure 4.7.1.6). Glass is selected from over a thousand entries in the International Glazing Database, providing the optical properties of the glass. The physical properties of the glass are in the simulation's material database. Properties of a database selection can be viewed by clicking on the "Details" icon, revealing a table of the selection's properties (Figure 4.7.1.7). Selections from the databases are made using the "Select" icon, which displays a table of the materials and their properties in the database (Figure 4.7.1.8). The properties can be reviewed to guide the selection.

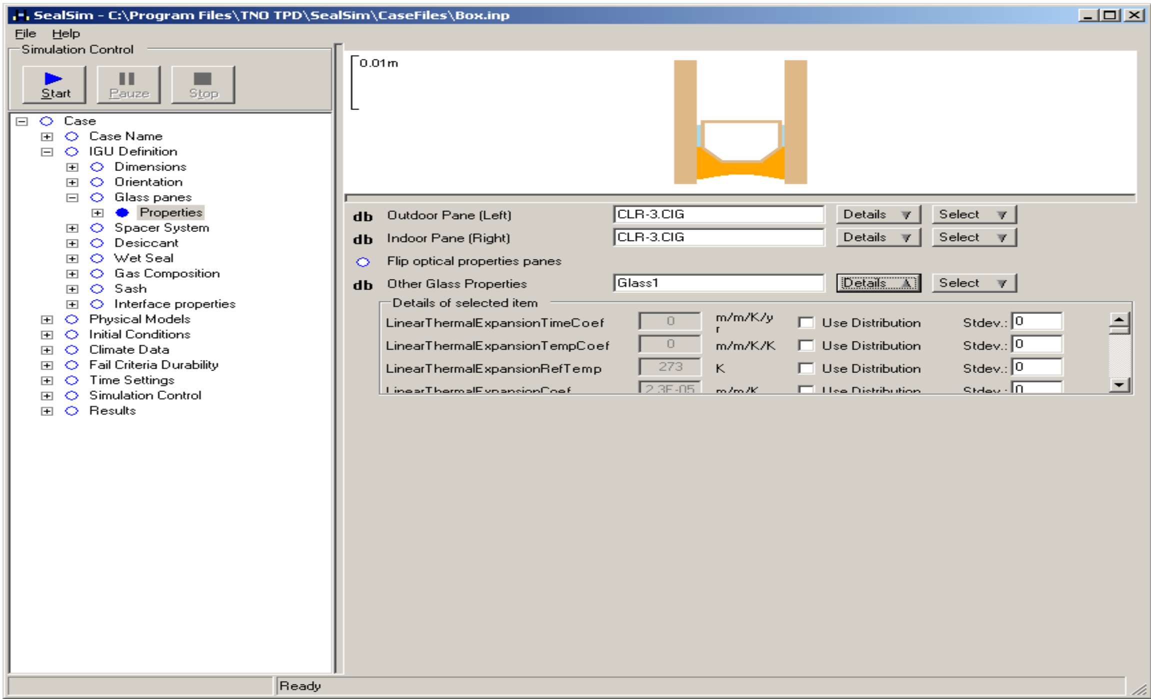


Figure 4.7.1.7 IG unit Definition - Glass Lites and Properties Selection Screen

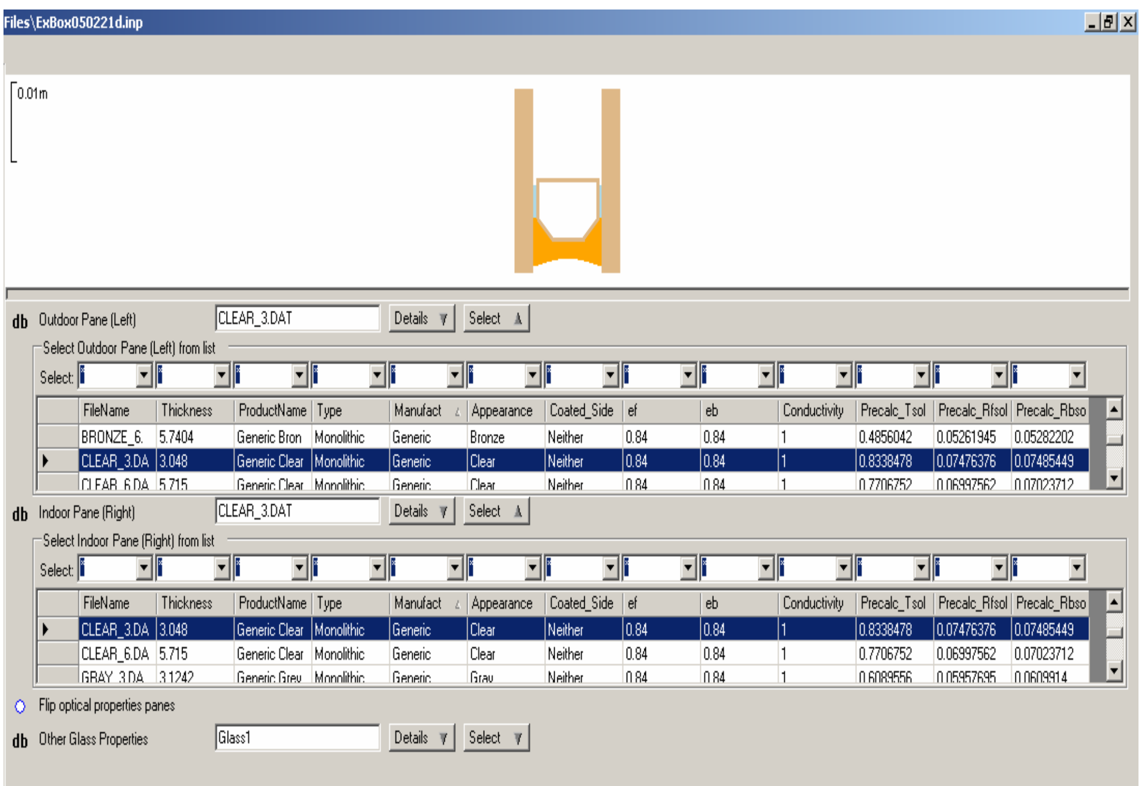


Figure 4.7.1.8 Detail of Glass Selection - Glass Lites Selection Screen

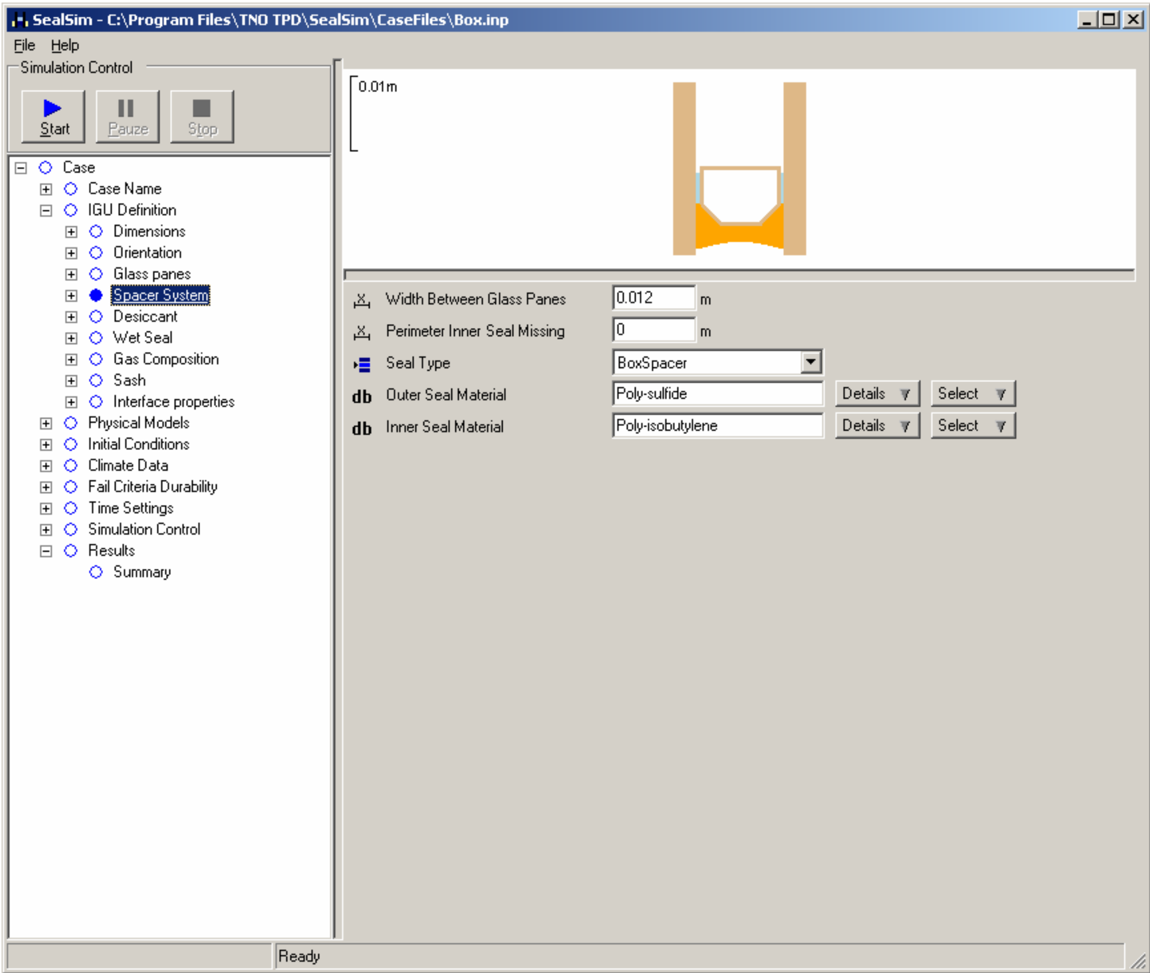


Figure 4.7.1.9 **Spacer System input screen**

The spacer and seals are defined in the "Spacer System" node (Figure 4.7.1.9). The selection of a box or TPS type spacer is made in this window as well as the selection of the inner and outer sealant materials from the database. In addition, the width between the glass lites is specified and the amount of missing inner sealant (due to corner keys, etc.) is defined.

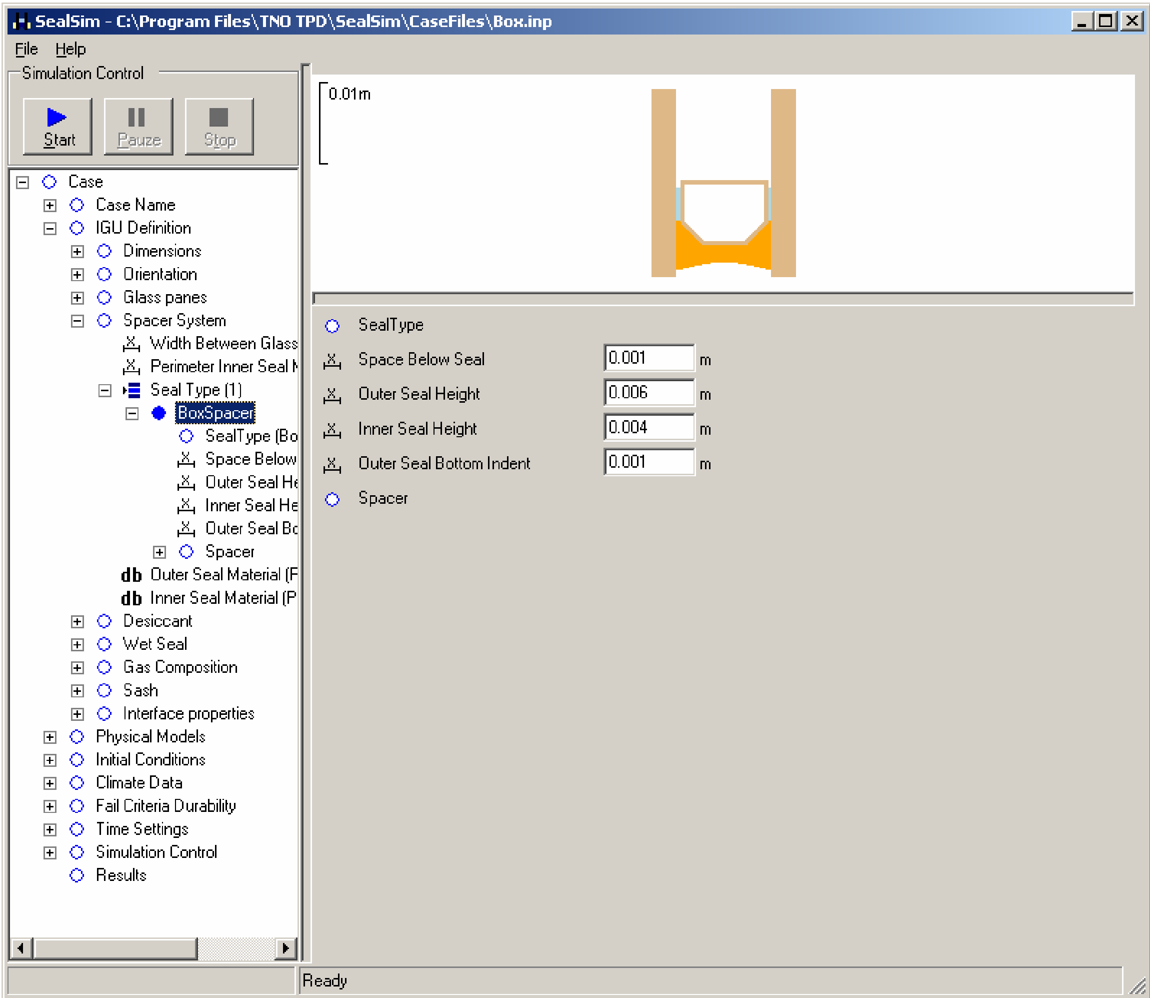


Figure 4.7.1.10 **Seal dimension input screen – box spacer**

The heights of the inner and outer sealants are defined under the “Seal Type” sub node. The box spacer system is shown in Figure 4.7.1.10. The thickness of the sealant for the box spacer system is defined using the distance between the glass along with the spacer dimensions and spacer placement (Figure 4.7.1.11). Once entries are made in this node, a graphic of the IG unit being assembled is shown.

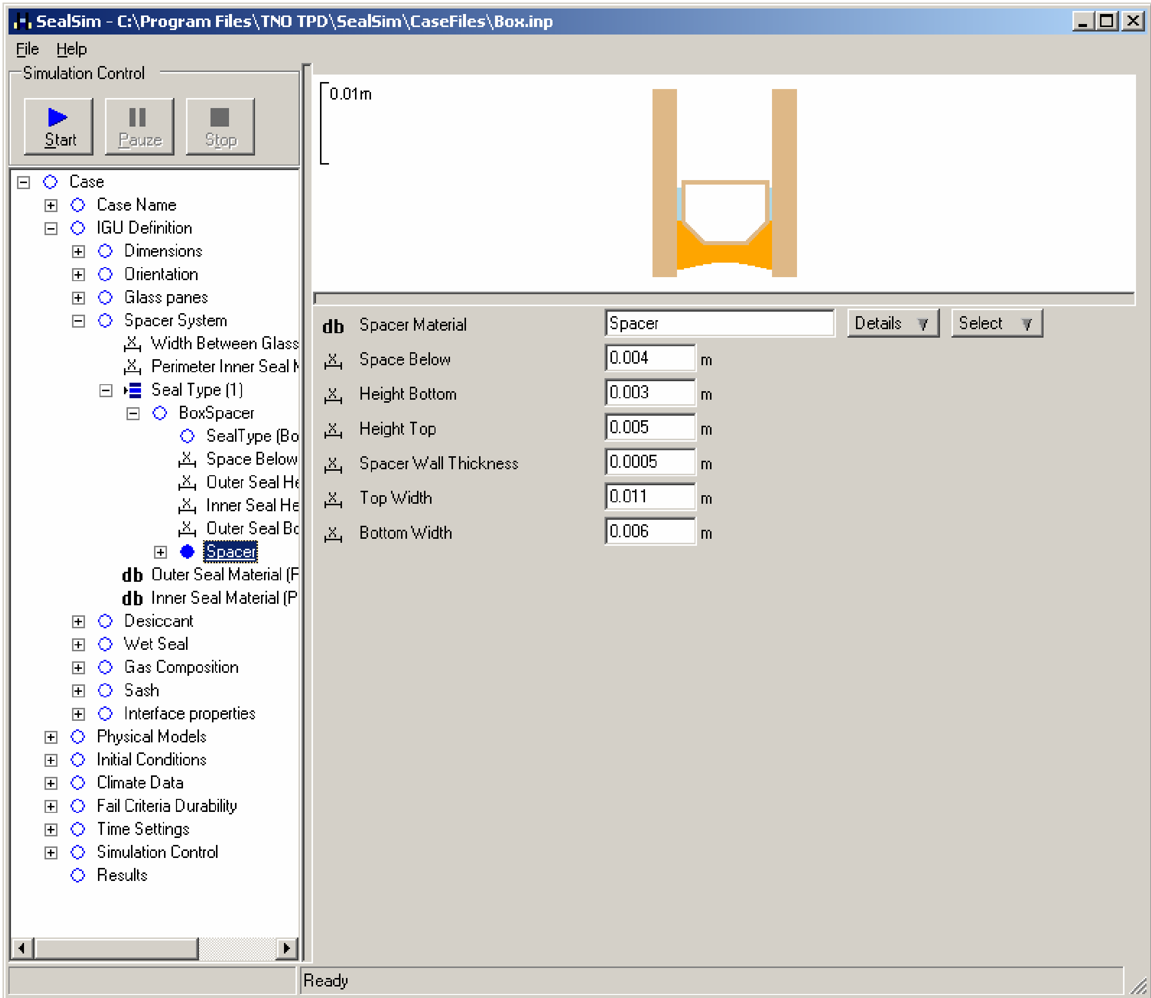


Figure 4.7.1.11 **Spacer dimension input screen - box spacer**

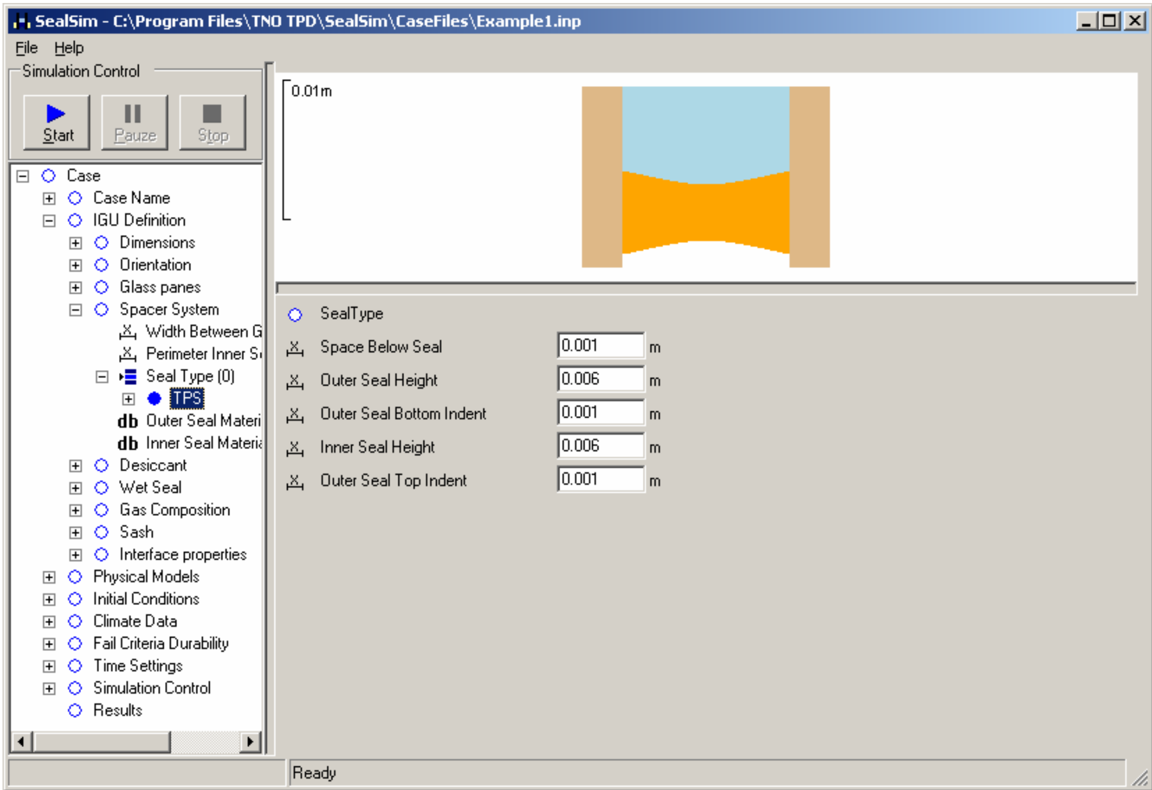


Figure 4.7.1.12 Seal dimension input screen – TPS spacer system

The appearance of the 'Seal Type' sub node for the TPS spacer system is shown above in Figure 4.7.1.12. The width of the TPS spacer system is determined by the distance between the glass lites.

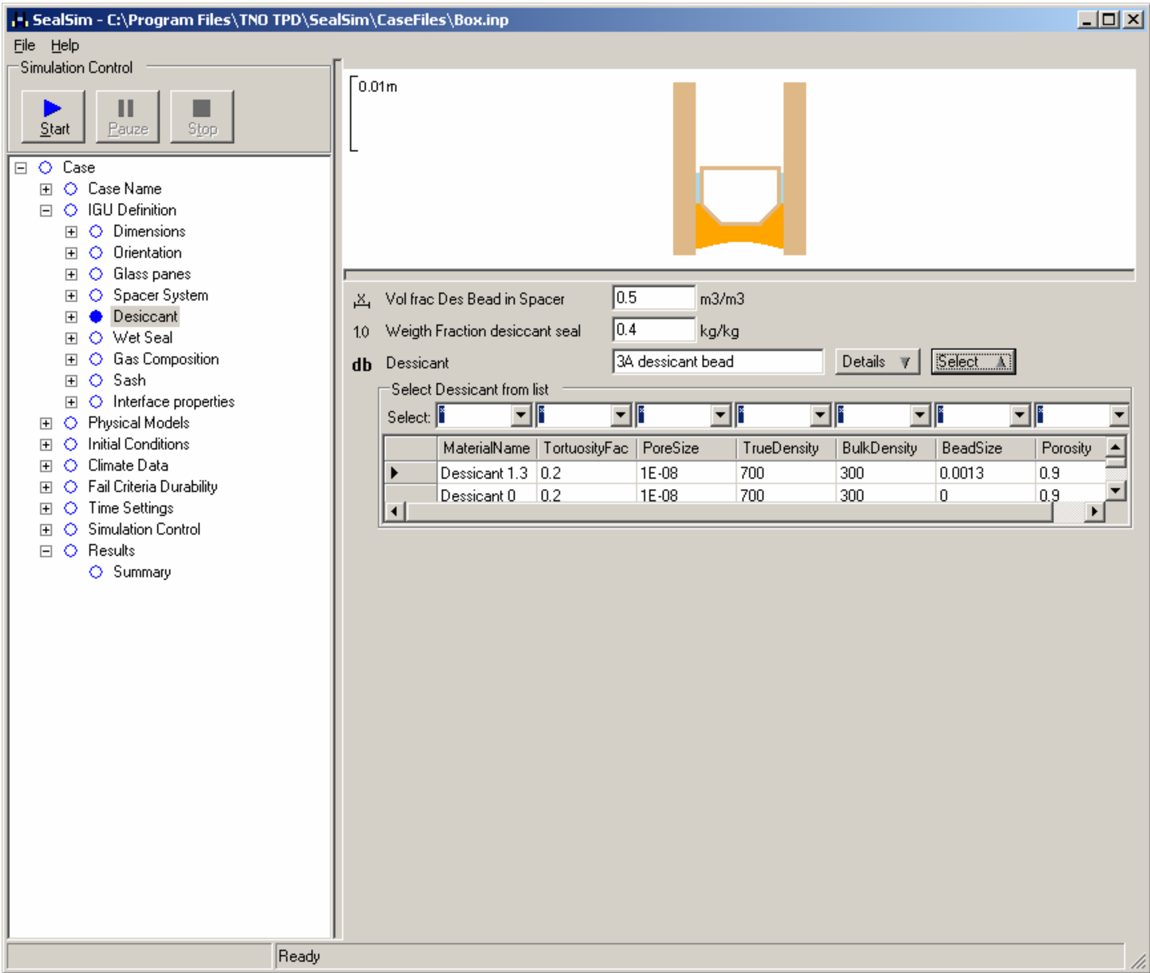


Figure 4.7.1.13 Desiccant input screen

The Desiccant node (Figure 4.7.1.13) is used to define the loading and type of desiccant used in the simulation.

For the **box spacer system**, the desiccant loading is made on a **volumetric basis** taking into account the desiccant bead size and bulk density along with the internal dimensions of the spacer.

The desiccant loading of the **TPS spacer system** is made on a **weight fraction basis** of the desiccant in the inner sealant material along with the inner sealant dimensions.

For both spacer systems, the type of desiccant is selected from the desiccant materials database.

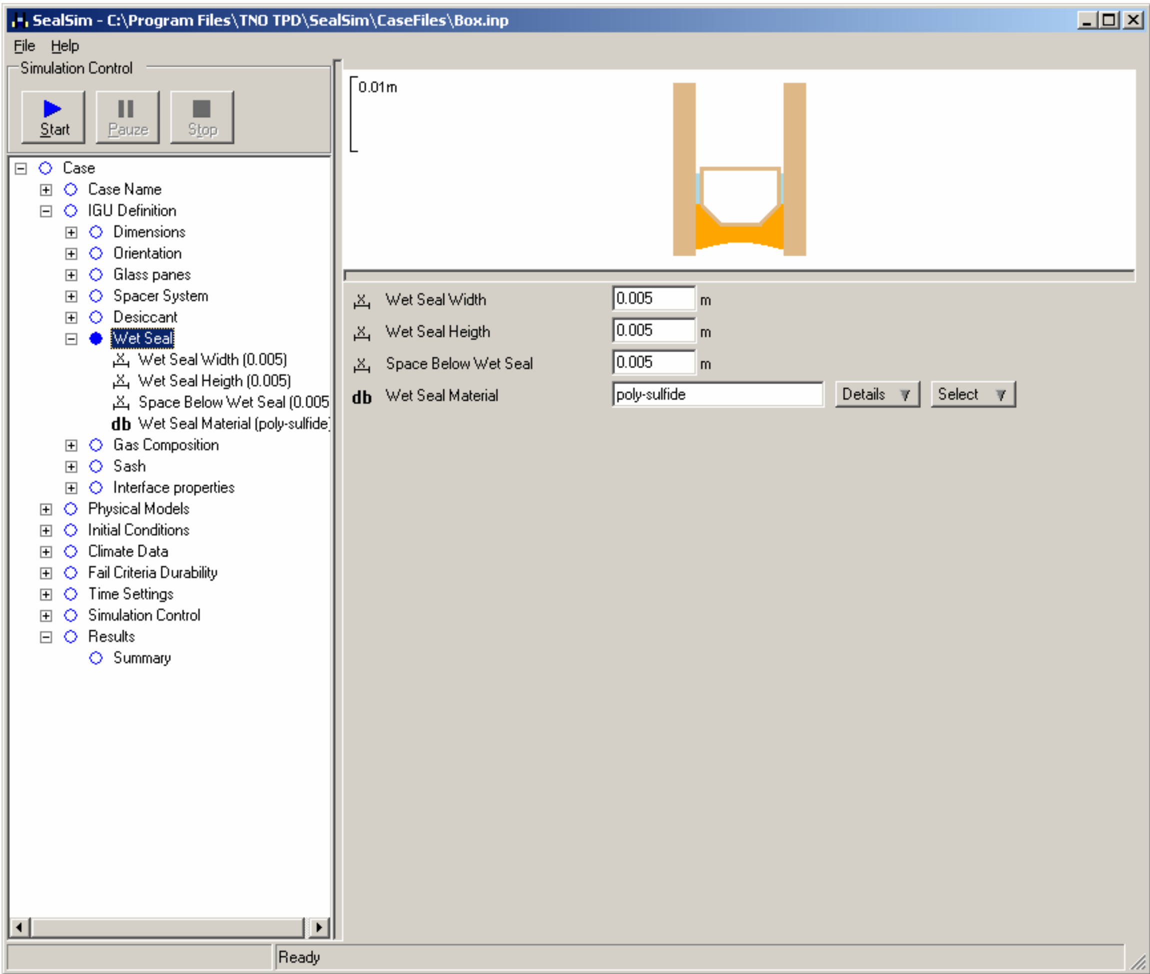


Figure 4.7.1.14 Wet Seal input screen

The Wet Seal node (Figure 4.7.1.14) is used to define the dimensions and properties of the material used to glaze the IG unit in the window sash. This field is not limited to wet glazing materials. The user could add other glazing materials, such as tapes or gaskets, to the materials database and define and use this node to define their dimensions.

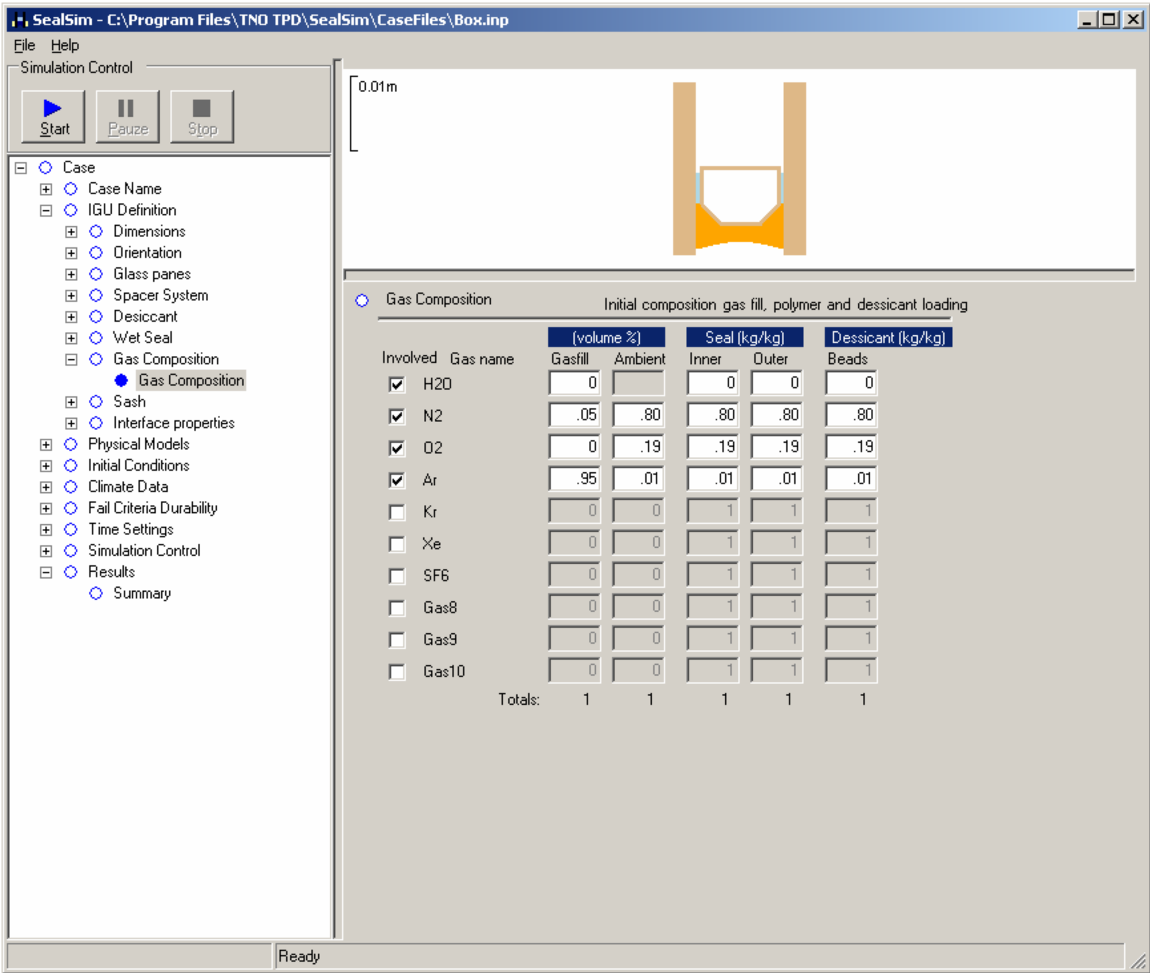


Figure 4.7.1.15 Gas Composition input screen

The Gas Composition node (Figure 4.7.1.15) is used to define the gases used in the simulation. The user can choose up to ten gases to be used in the simulation. For gases chosen, the initial gas make-up in IG unit air space, dissolved in the sealants, absorbed by the desiccant and surrounding the IG unit are defined.

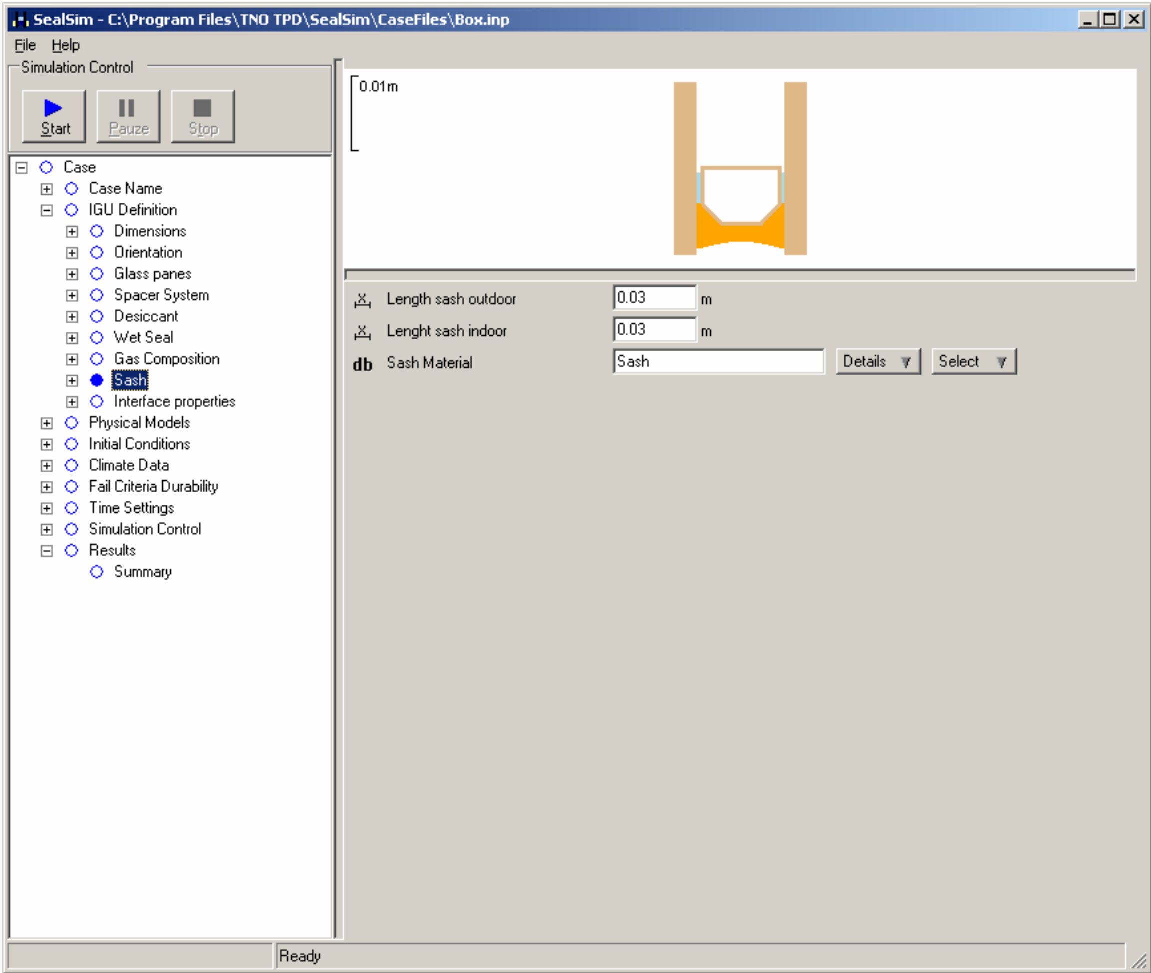


Figure 4.7.1.16 Sash input screen

The Sash node (Figure 4.7.1.16) is used to define the dimensions of the sash surrounding the IG unit and select the sash material from the database. The 'select' icon is used to view and select from the entries in the database and the 'Details' icon can be used to view the properties of the selected material.

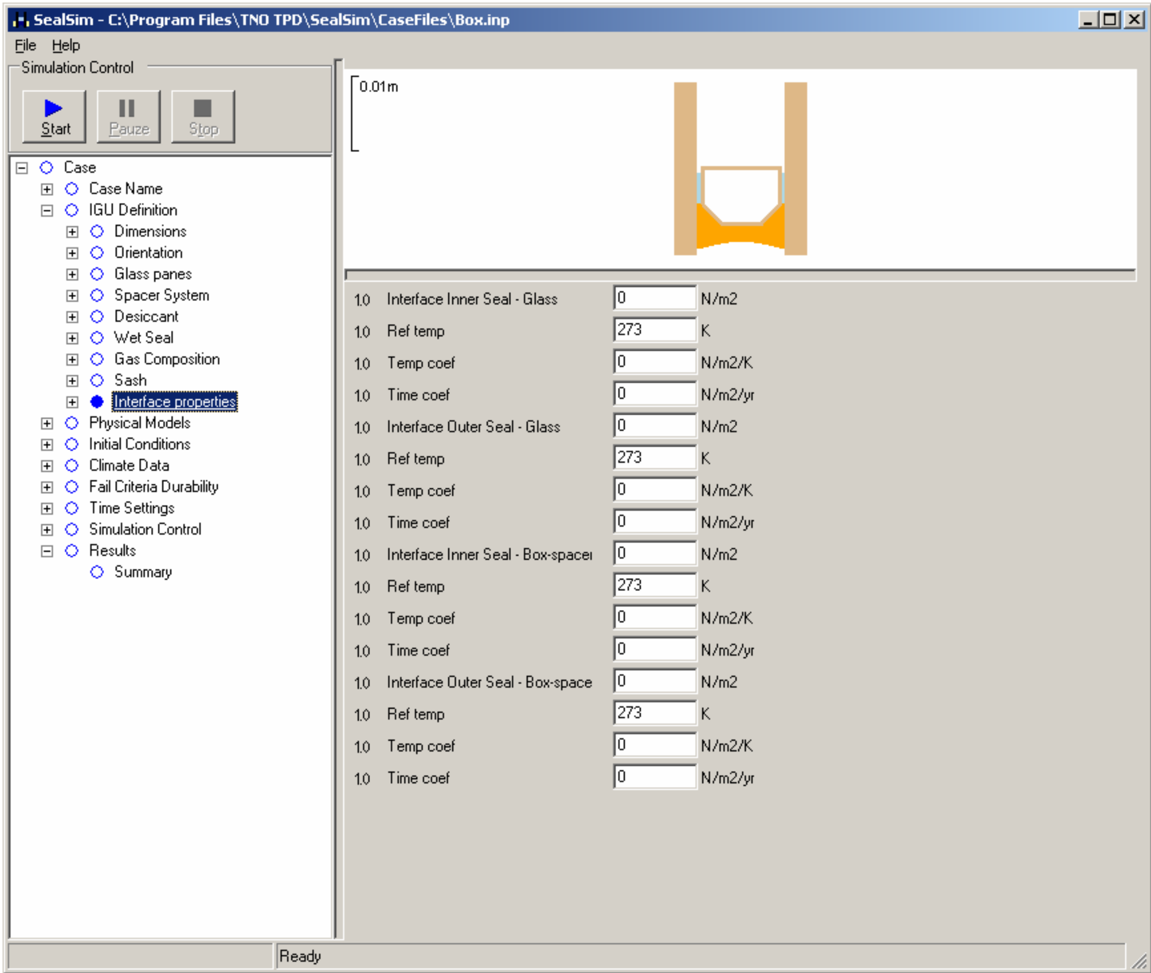


Figure 4.7.1.17 Interface properties input screen

The Interface Properties node (Figure 4.7.1.17) is used to define the adhesion strength between the inner and outer sealants to the glass and for a box spacer, the adhesion of the sealants to the spacer.

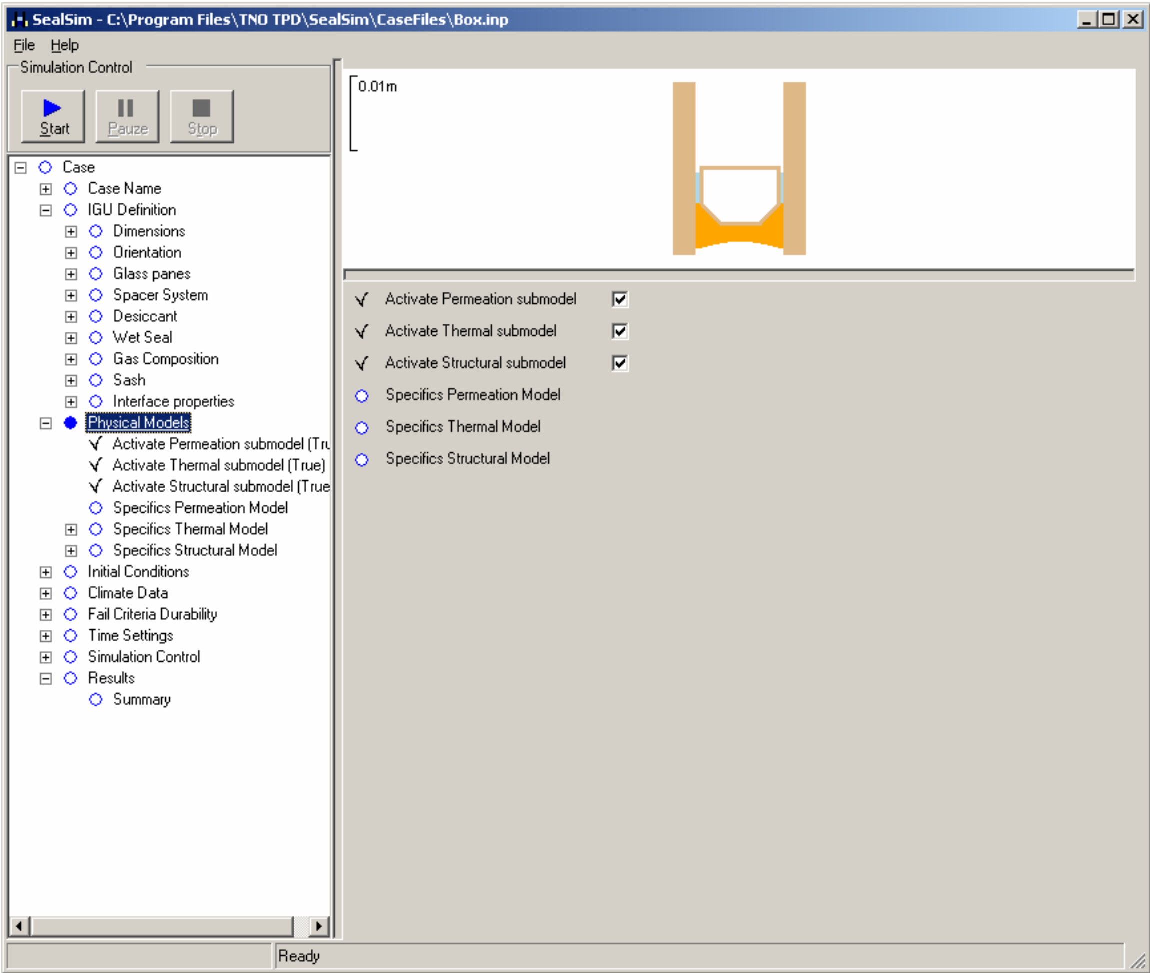


Figure 4.9.1.18 Physical Models selection screen

The Physical Models screen (Figure 4.7.1.18) is used to select which of the physical models will be run during the simulation. The permeation, thermal and structural models can be run either alone or together, in any combination.

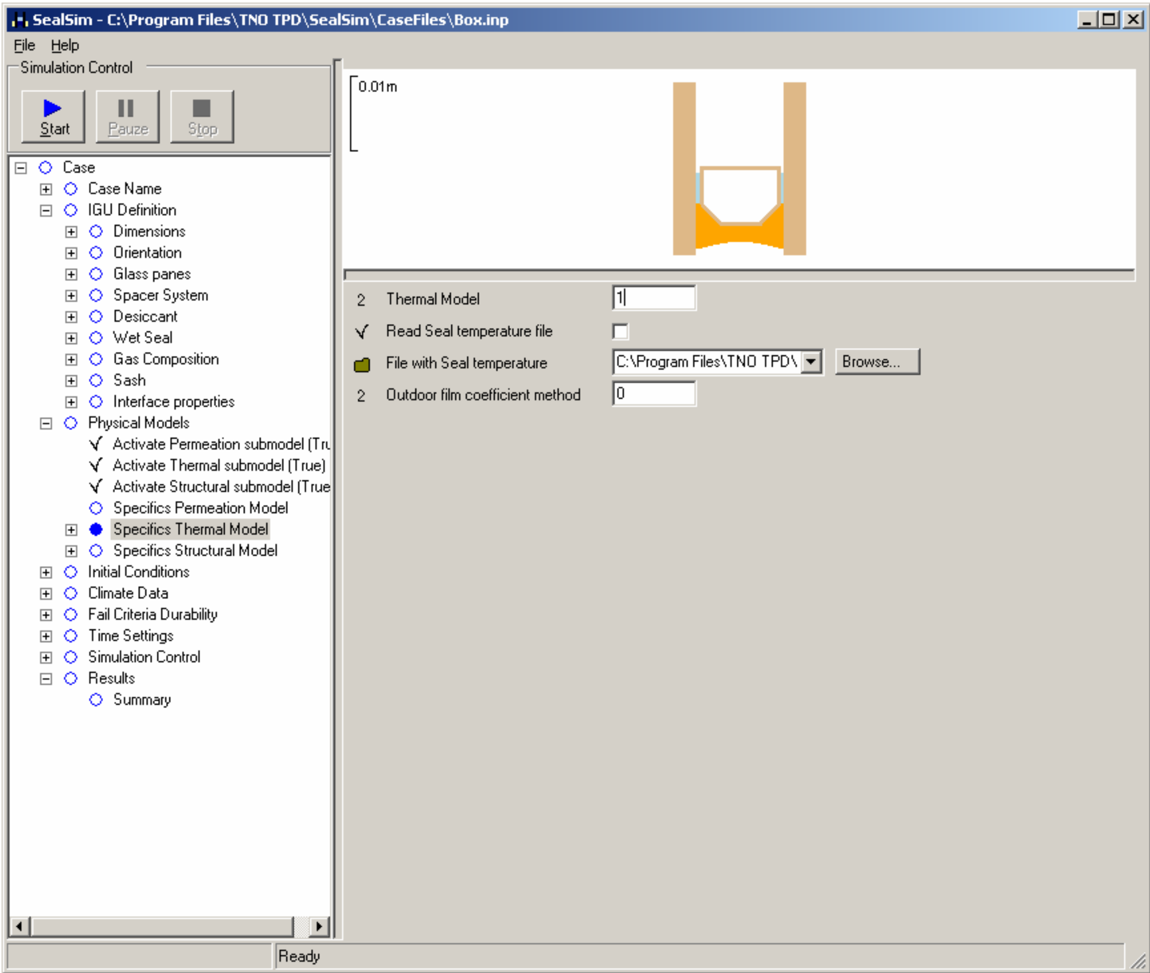


Figure 4.7.1.19 Thermal Model Specifics screen

In the Thermal Model Specifics node (Figure 4.7.1.19) options are given and the choice of the thermal model is made. A file can be designated for use by the simulation for the seal temperature rather than using the simulation's calculated seal temperature. The method for determining the outdoor film coefficient can be made from four choices.

0 = ISO 15099

-1 = Old ASRAE SPC 142 correlation

-2 = Yazhanian-Klems correlation

-3 = Kimura correlation

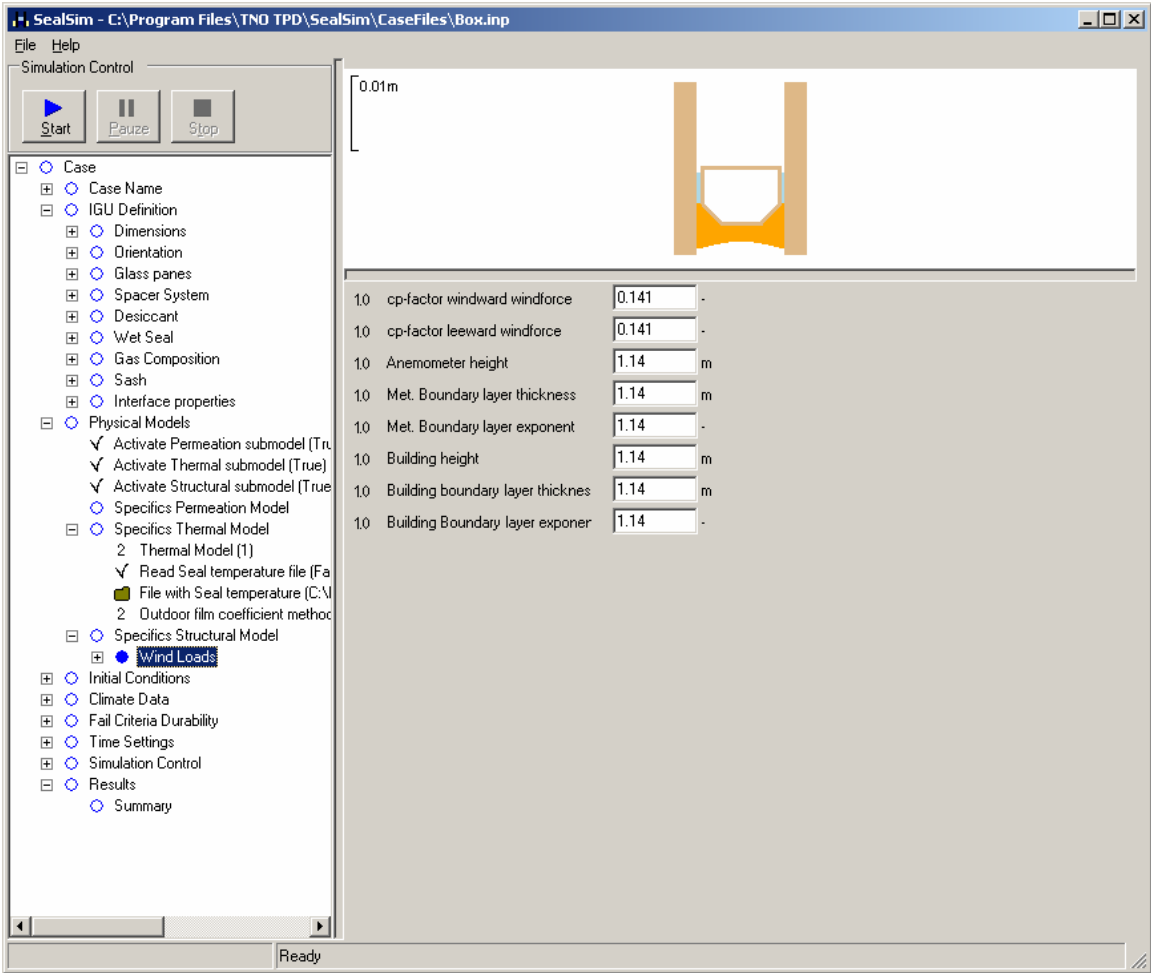


Figure 4.7.1.20 Structural Model Wind Loads Screen

The Structural Model Specifics node (Figure 4.7.1.20) provides the inputs for the simulation to determine the wind loading on the IG unit as a function of the wind speed and direction (from the climate file) and the orientation of the window. Details on these inputs can be found in the ASHRAE Fundamentals Handbook. Future versions of the simulation software will allow the use of other wind load data such as that derived from ASCE 7. It is required that the wind data be presented in the TMY2 format as described.

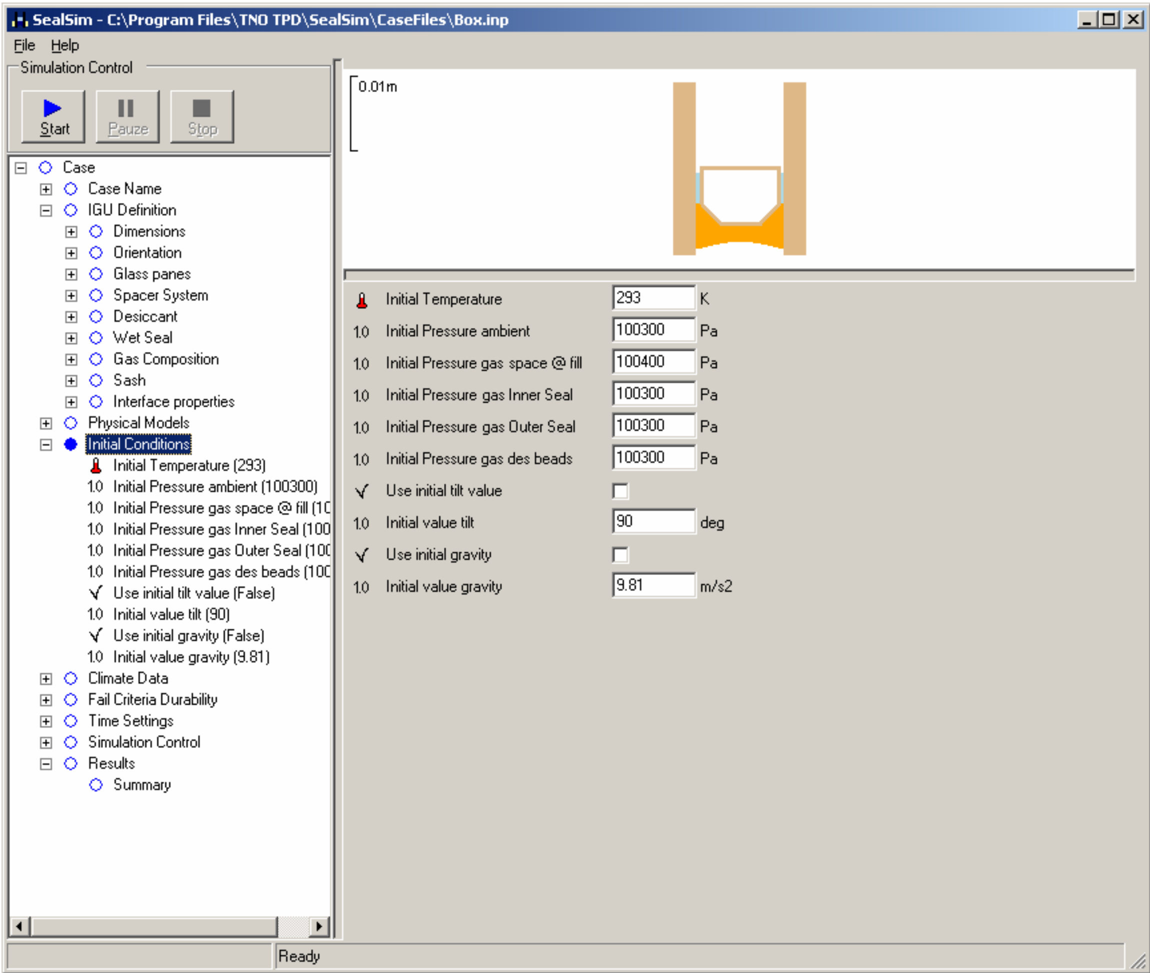


Figure 4.7.1.21 Initial Conditions Input Screen

The Initial Conditions node (Figure 4.7.1.21) defines the initial temperature and gas pressures at the beginning of the simulation. This includes the pressure within the air space of the IG unit as well as the pressure within the sealants and on the desiccant. An IG unit tilt angle other than the installation angle can be used as an initial value and the simulation can be started with or without gravitational stresses acting on the system during the initial time step.

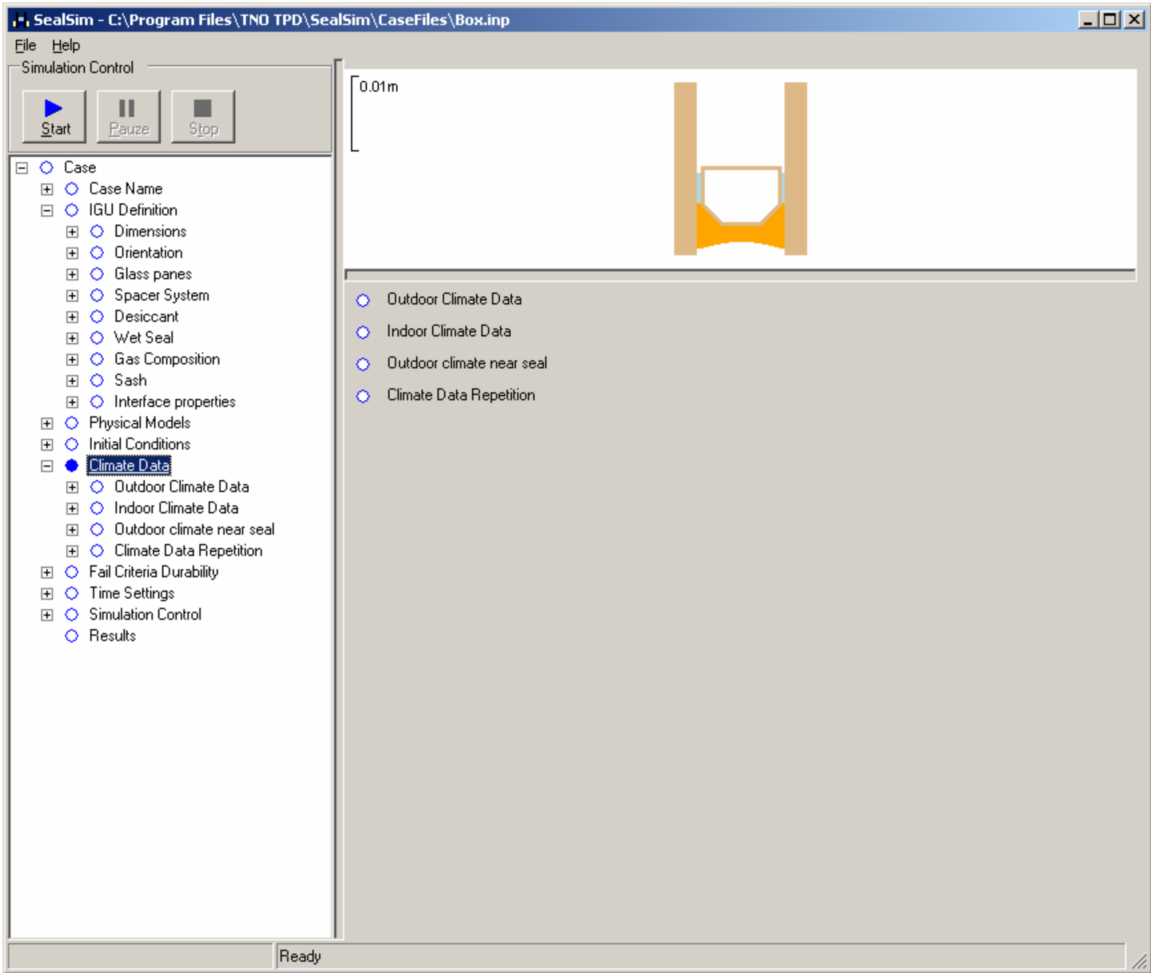


Figure 4.7.1.22 Climate Data Node Overview

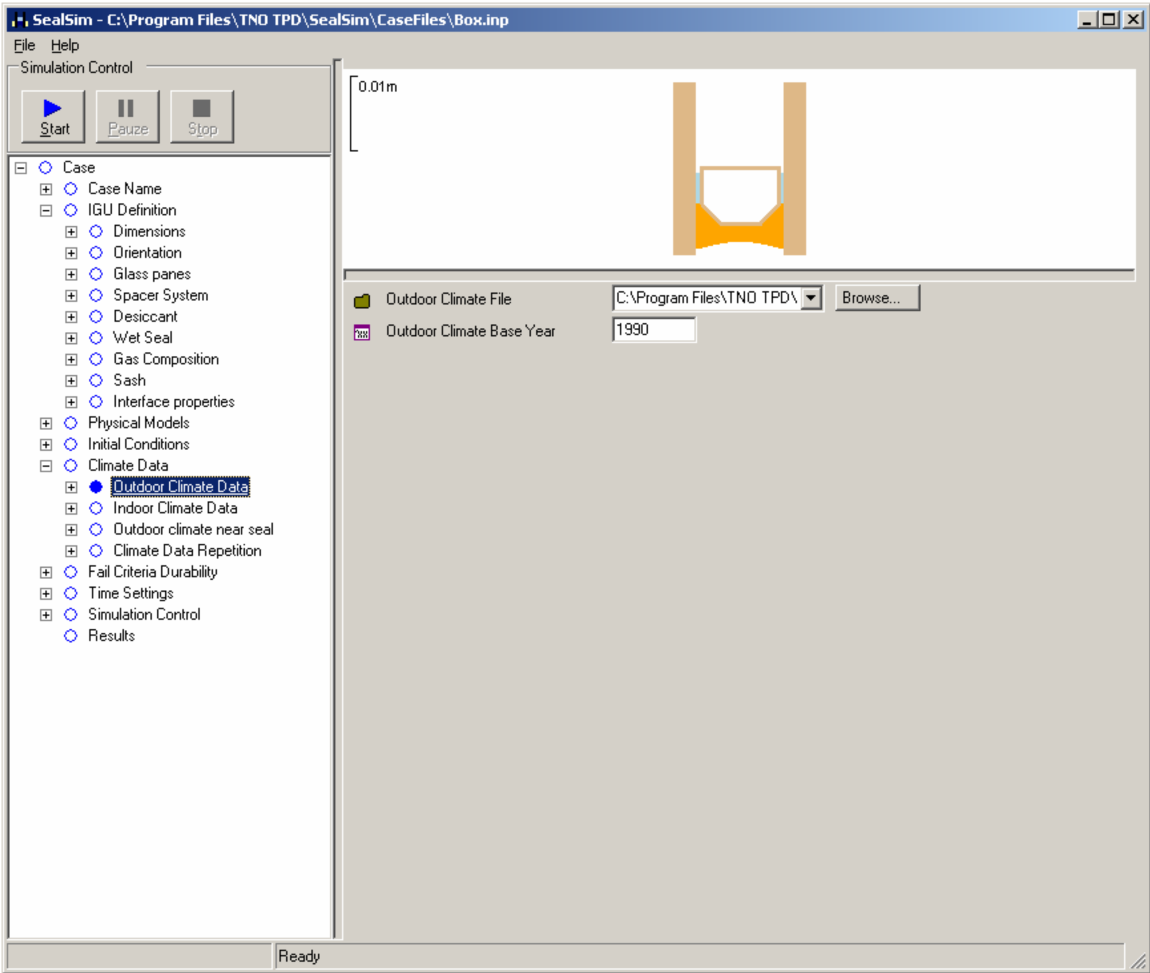


Figure 4.7.1.23 Outdoor Climate Data Input Screen

The Outdoor Climate Data sub node (Figure 4.7.1.23) is used to select the data file the simulation will use to apply the environmental stressors to the IG unit. These climate data files must be in the format used for Typical Meteorological Year (TMY2) data files. The simulation uses the TMY2 format climate file to define the longitude, latitude, time zone and elevation of the IG unit. In addition hourly data for the dry bulb temperature, relative humidity, barometric pressure, wind speed and direction, direct normal radiation and total sky cover are used.

Additional information on the TMY2 format and creation or modification of the climate files can be found in the Section 4.5.1 of the User Manual Appendix 3.

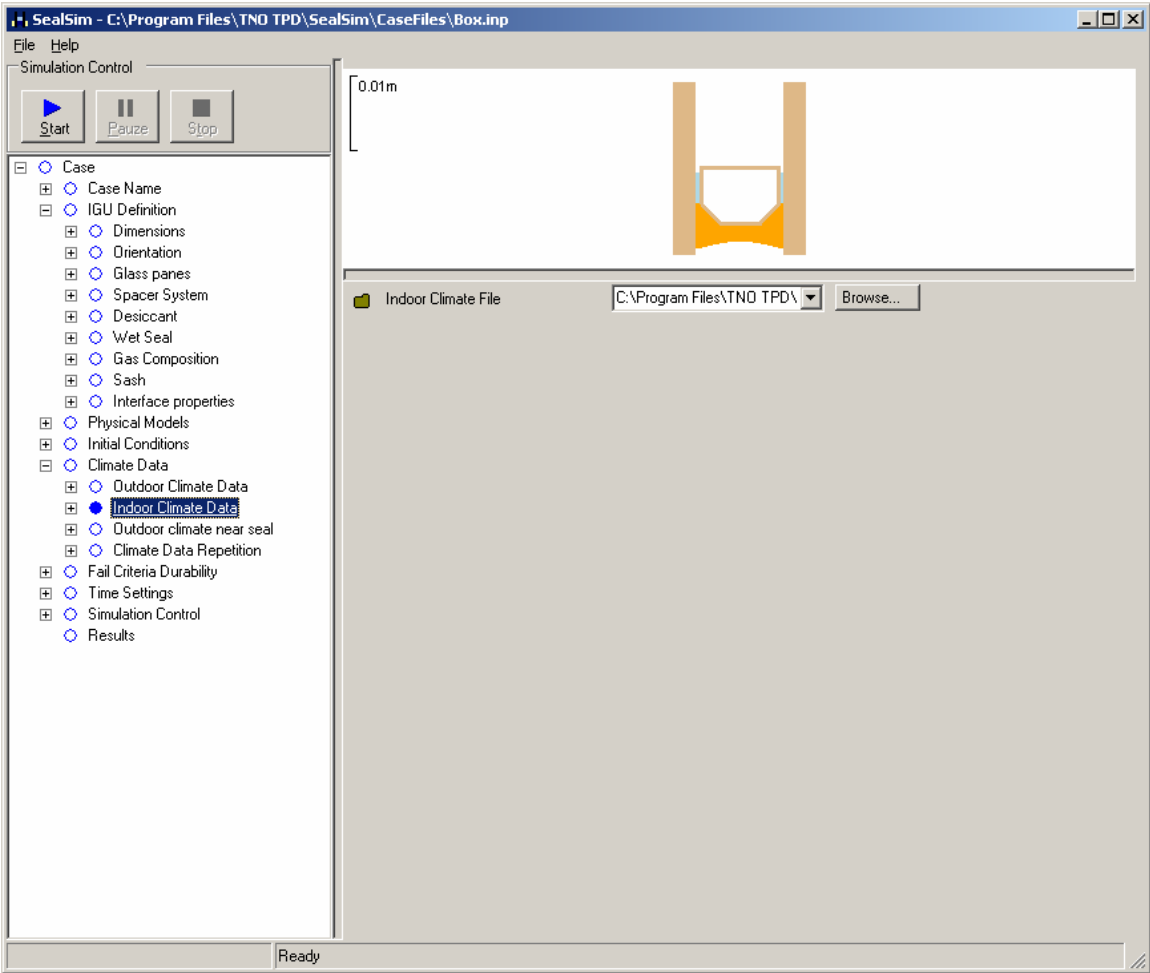


Figure 4.7.1.24 Indoor Climate Data Input Screen

The Indoor Climate node (Figure 4.7.1.24) is used to select the data file which will define the indoor climate during the simulation. This file includes data on the indoor air temperature, relative humidity, radiative surface temperature and wind speed. An example of the indoor data file format (included with the simulation) is shown in Section 4.5.7 of the User Manual, Appendix 3.

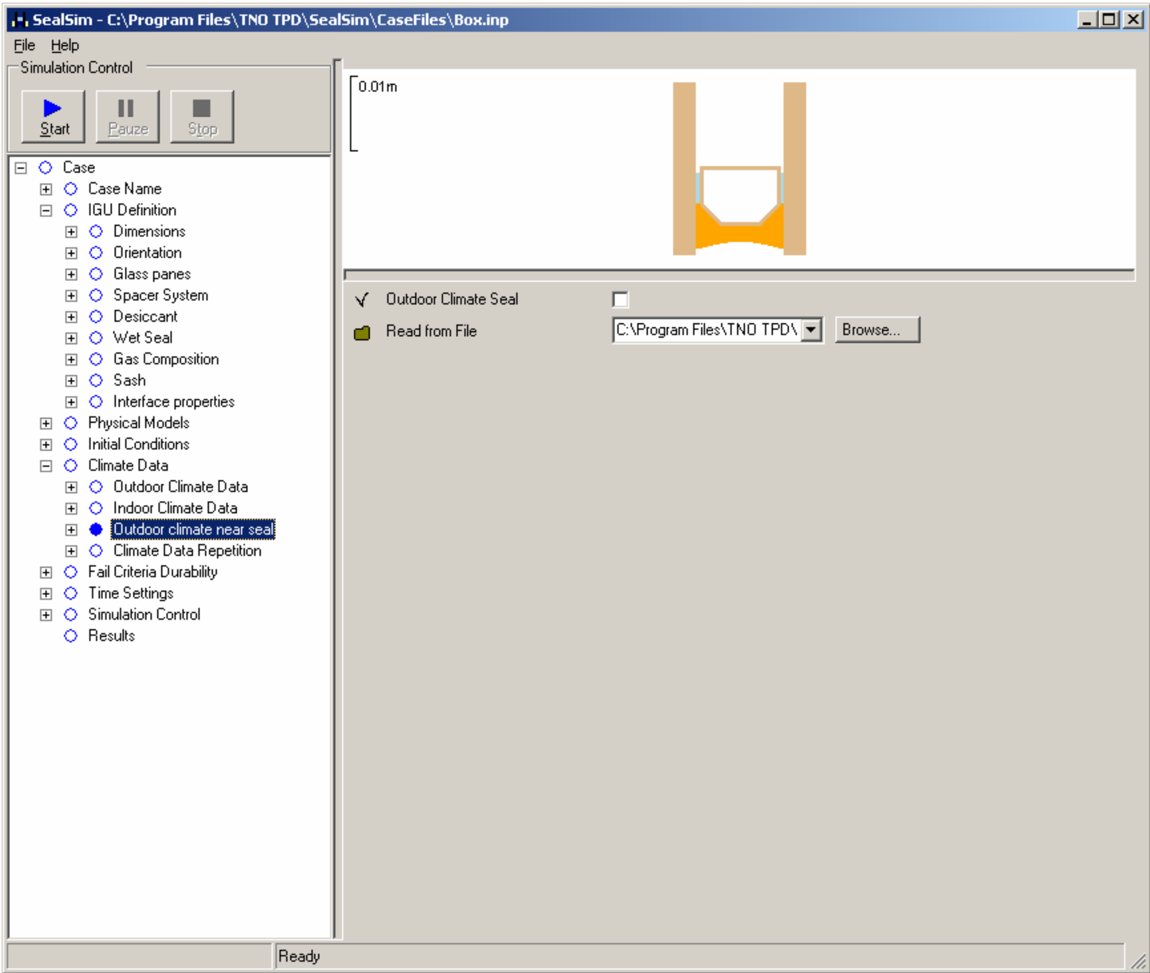


Figure 4.7.1.25 Climate, Near Seal Input Screen

The Climate "Near" Seal node (Figure 4.7.1.25) provides the option of defining an alternative temperature and relative humidity in the area near the seal. The simulation normally defines the humidity near the seals as a function of the outdoor humidity. An alternative humidity near the seal can be defined using this option. For example, this option could be used to evaluate the impact of high humidity due to water trapped in the glazing rebate.

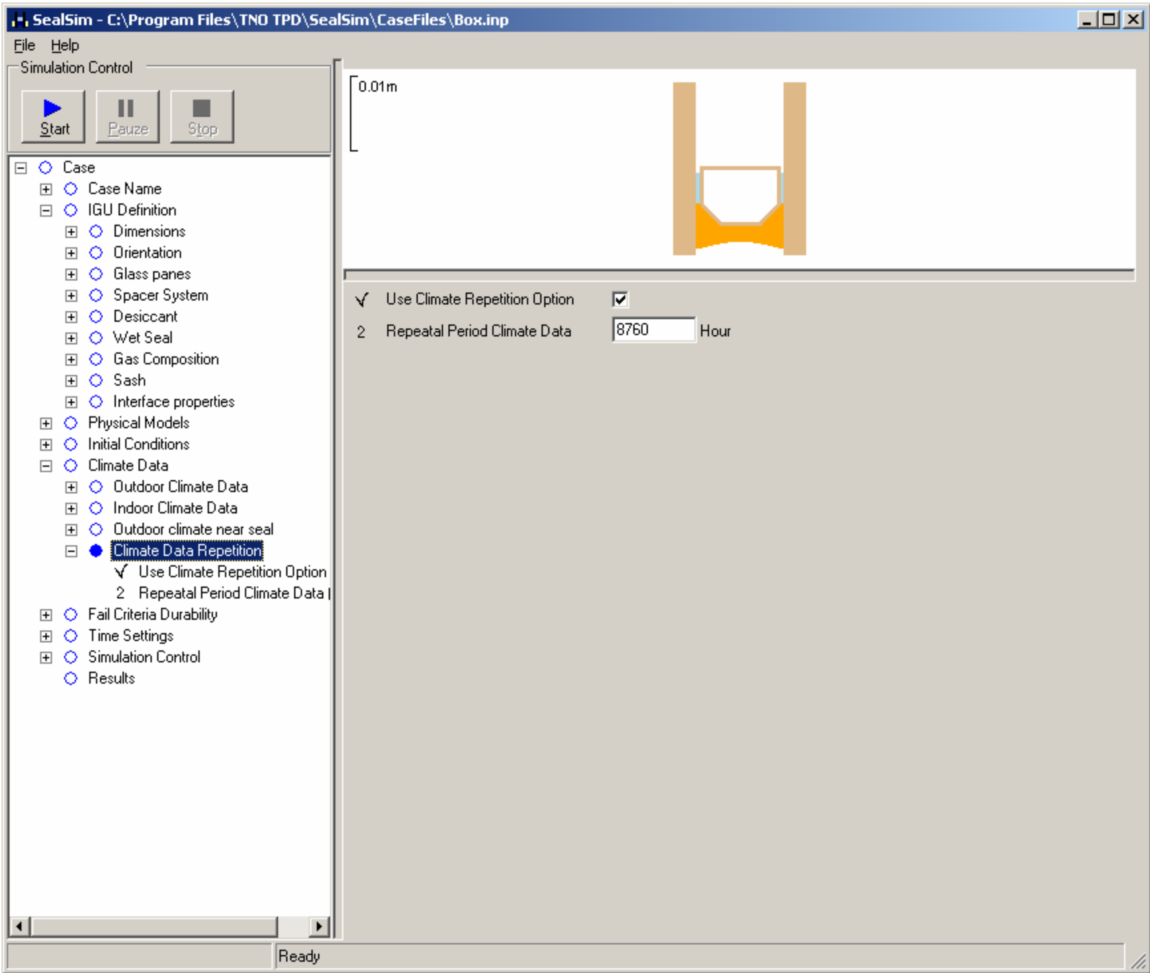


Figure 4.7.1.26 Climate Repetition Input Screen

The Climate Repetition node (Figure 4.7.1.26) is used to help define how much of the outdoor climate data file will be used during the simulation. Using this option, a one year simulation could read the TMY2 format climate data file once in total or repeat any length portion of the climate file for the one year simulation.

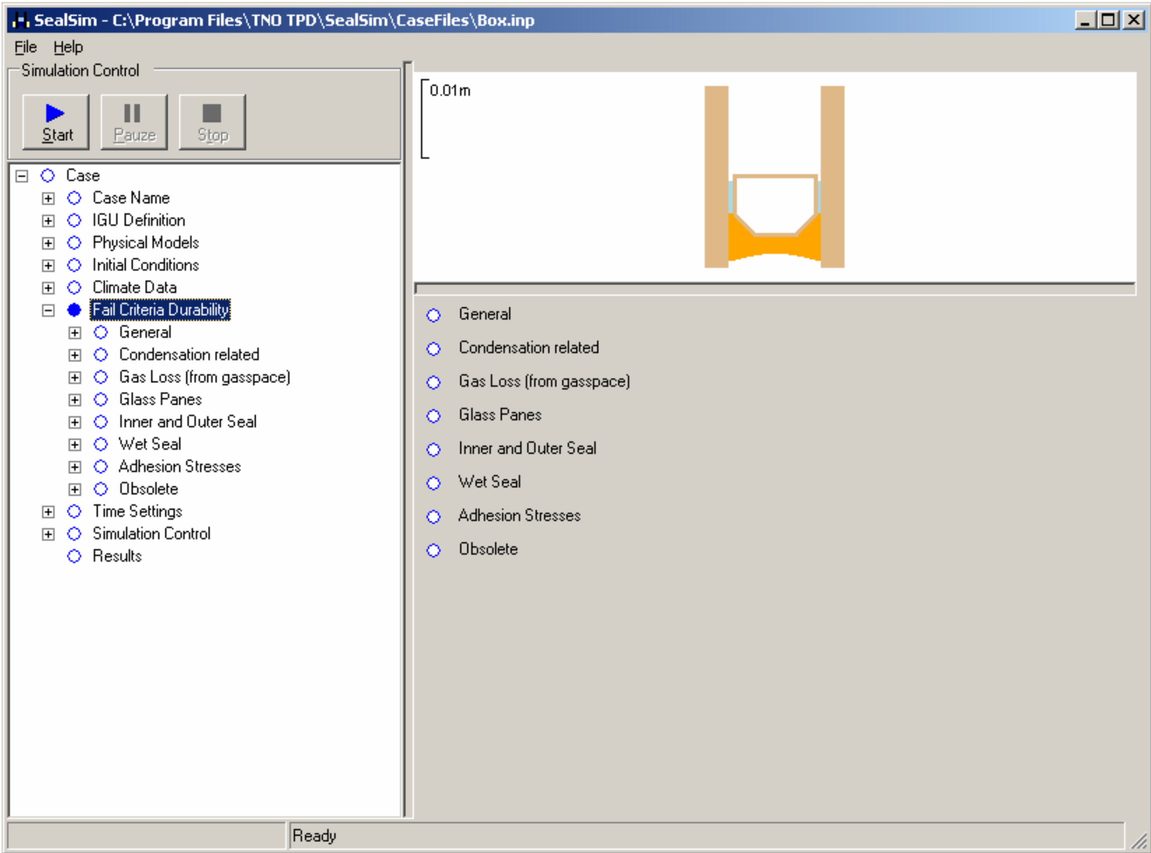


Figure 4.7.1.27 Failure Criteria Node Overview Screen

The Failure Criteria node (Figure 4.7.1.27) is used to set the failure criteria that the simulation will be monitoring. The IG unit failure criteria used by the simulation are broken down into seven sub nodes. The threshold level needed for a failure to be declared is either entered directly by the user or calculated from the properties of the materials selected for the simulation. During a simulation, when any of the selected failure criteria is met, the simulation will stop the current Monte Carlo run, record the type of failure and time to failure and begin the next Monte Carlo run. The failure criteria sub nodes are shown below.

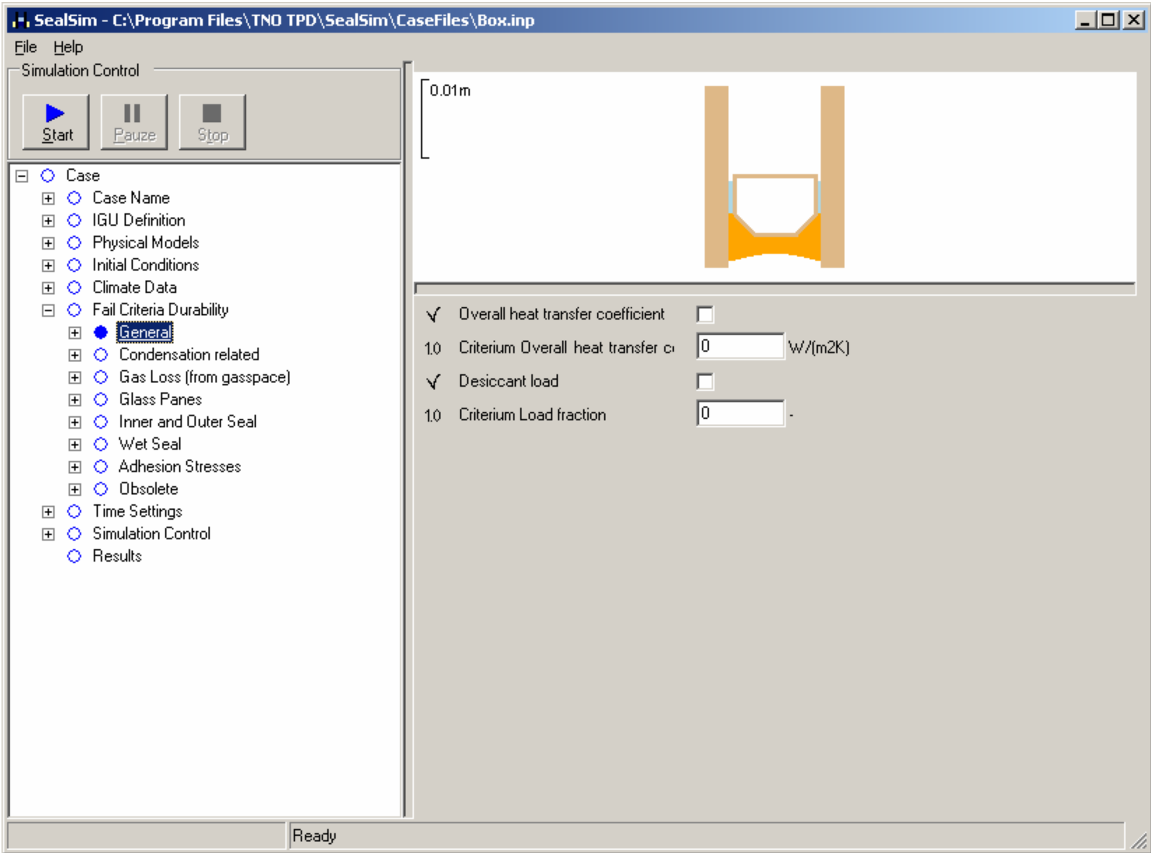


Figure 4.7.1.28 Failure Criteria - General Screen

The General Failure Criteria Sub node contains the heat transfer coefficient and the desiccant loading. For all failure criteria, the sub node is activated by 'left clicking' in the check box. The heat transfer coefficient is an instantaneous value which is calculated using the average glass separation and the simulation's interior and exterior temperatures and wind speeds at the current time step in the simulation. Similarly, the desiccant loading is based on the weight fraction of water adsorbed on the material at the current time step in the simulation.

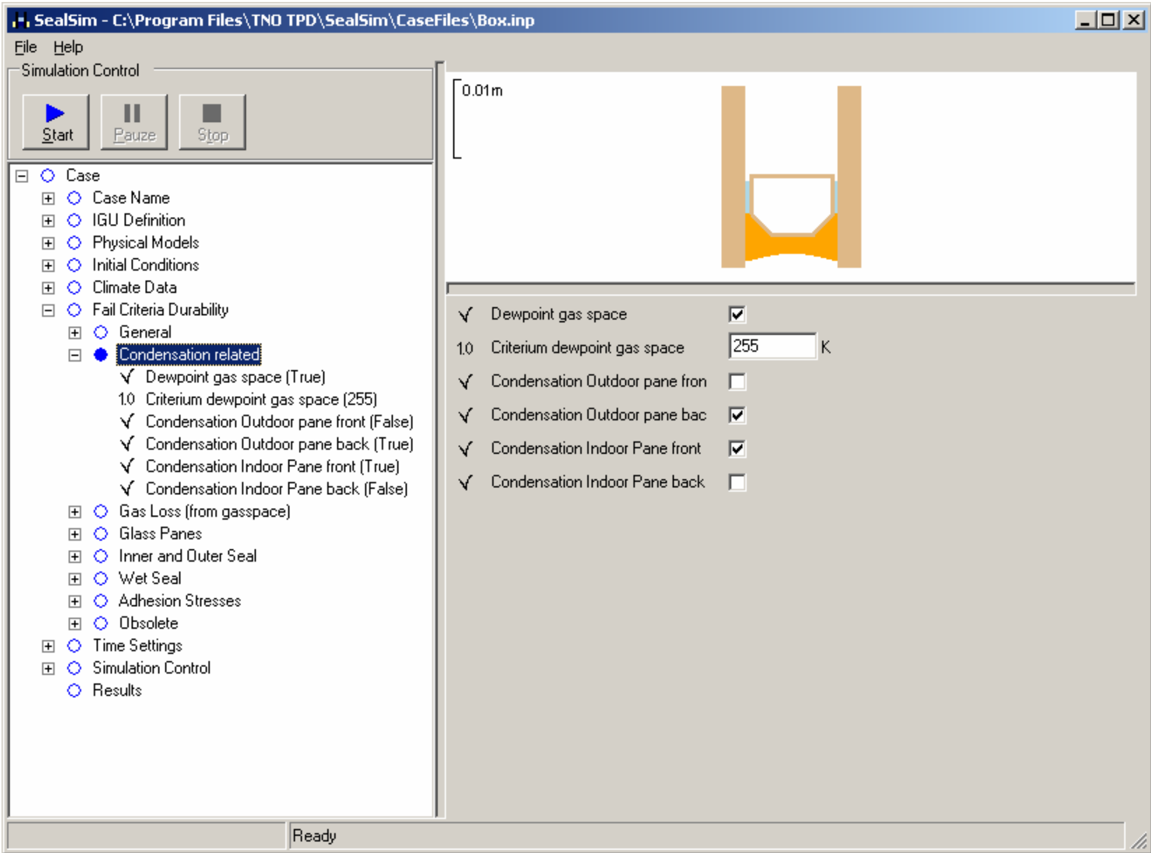


Figure 4.7.1.29 Failure Criteria - Dew Point and Condensation Screen

The Dew Point and Condensation Sub node is shown in Figure 4.7.1.29. The failure criterion for the gas space dew point is entered by the user. Condensation on all four surfaces of the IG unit can be selected. User input is not needed for the condensation failure criteria as they are determined based upon the temperature of the glass surface and the amount of water vapor in the gas surrounding the glass surface. Please note that the indoor glass lite condensation is not meant to simulate the onset of condensation at the edge of an IG unit. Such phenomena are driven by variables that are not modeled by the simulation (thermal bridge of the spacer, the temperature distribution within the IG unit and the cooling of the interior room air convectively flowing down the glass lite surface, etc.).

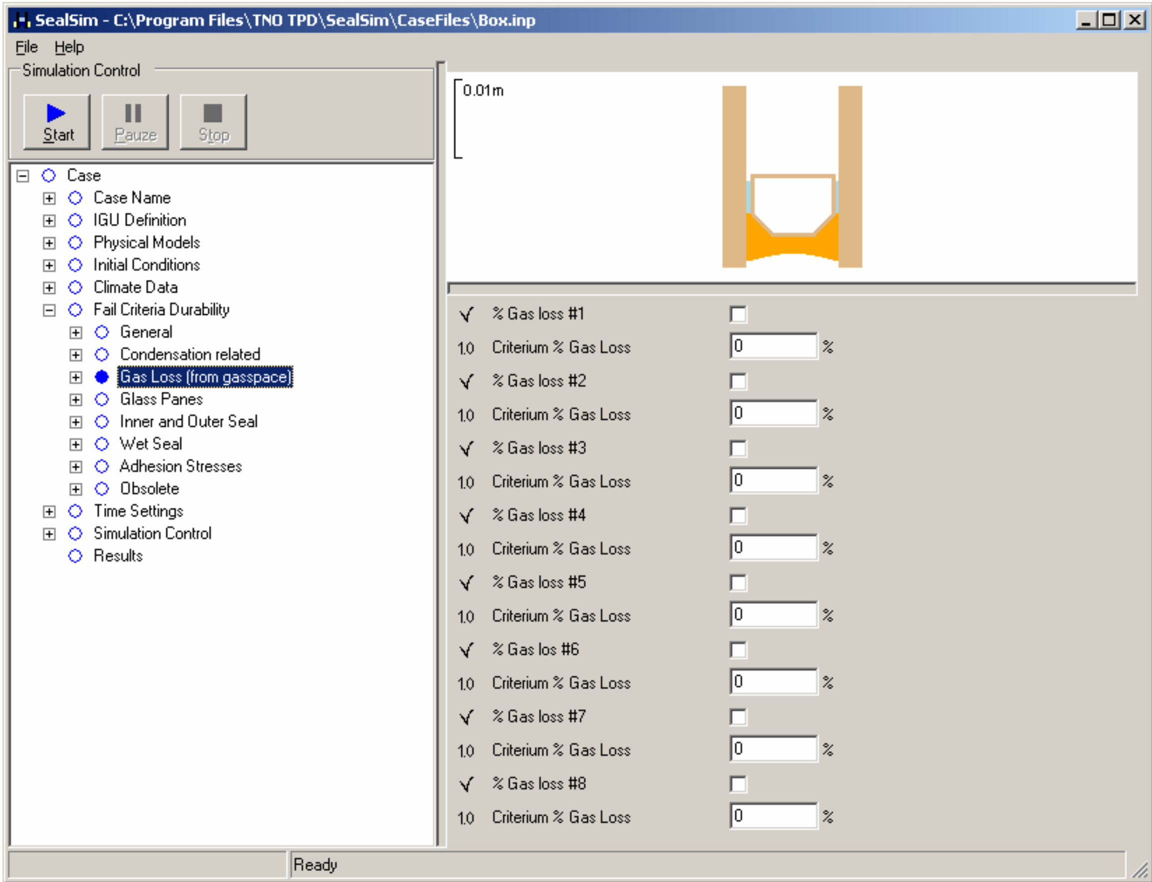


Figure 4.7.1.30 Failure Criteria - Gas Loss Screen

The Gas Loss sub node is shown in Figure 4.7.1.30. The gases are selected by checking the appropriate box and entering the desired value for the gas of interest. The failure criterion is the percentage of gas lost, based on the initial gas concentration, entered in the Gas Composition sub node.

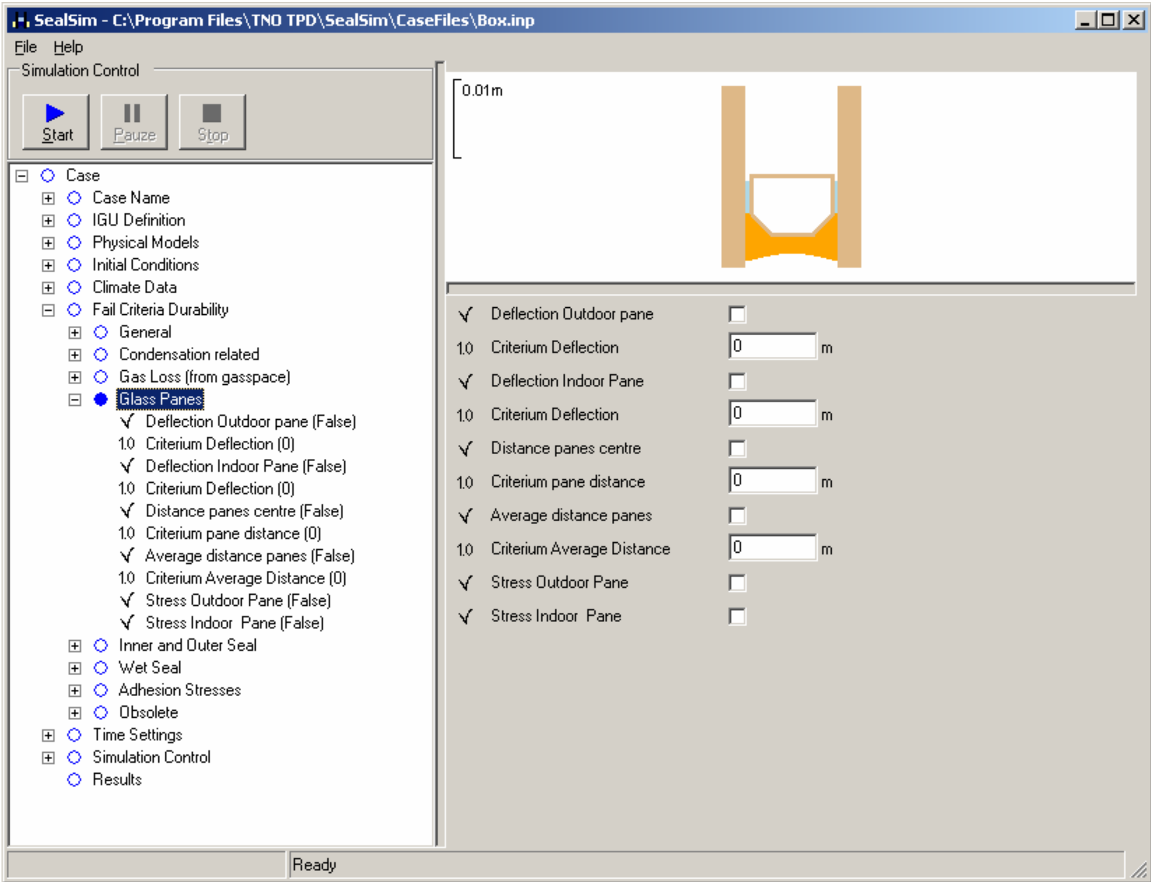


Figure 4.7.1.31 Failure Criteria - Glass Deflection and Stress Screen

The Glass Panes sub node is shown in Figure 4.7.1.31. This failure sub node monitors the deflection of the glass lites, the center of glass separation, and the average separation as well as the stress in the indoor and outdoor lites. The user enters the values for deflection and separation, while the stress threshold comes from the materials database.

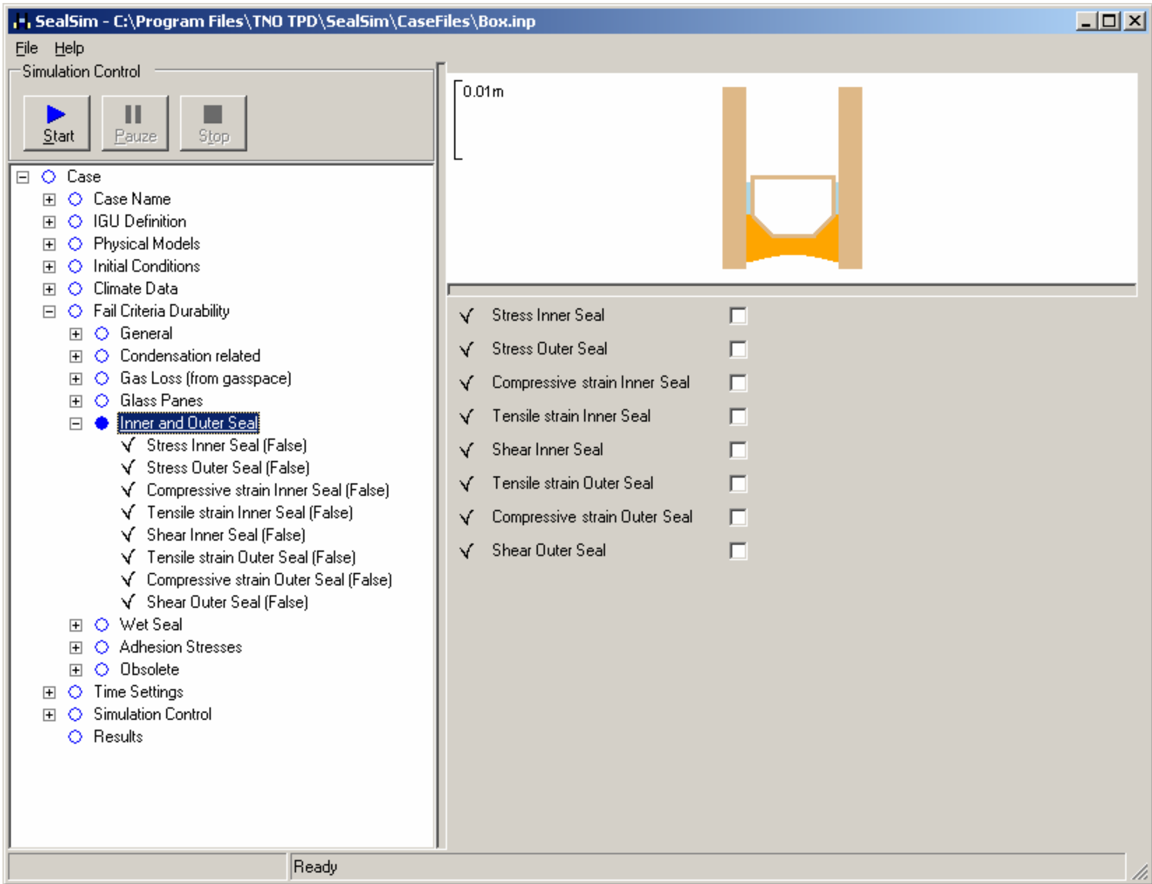


Figure 4.7.1.32 Failure Criteria - Inner and Outer Seal Selection Screen

The Inner and Outer Seal Failure sub node is shown in Figure 4.7.1.32. The user does not need to enter failure threshold values for these criteria as they are defined by the properties of the seal materials and the dimensions of the IG unit construction.

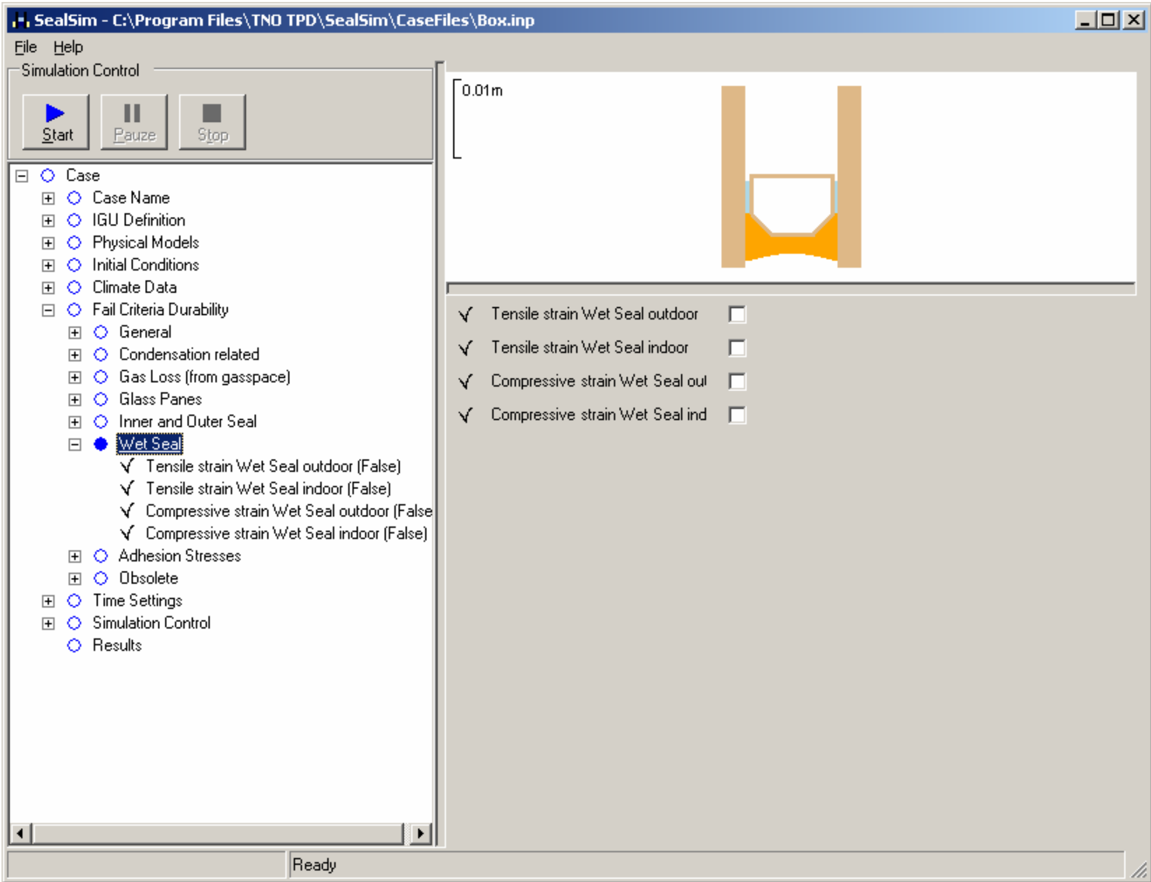


Figure 4.7.1.33 Failure Criteria - Wet Seal Selection Screen

The Wet Seal Failure sub node is shown in Figure 4.7.1.33. The user does not need to enter failure threshold values for these criteria as they are defined by the properties of the wet seal materials and the dimensions of the IG unit construction.

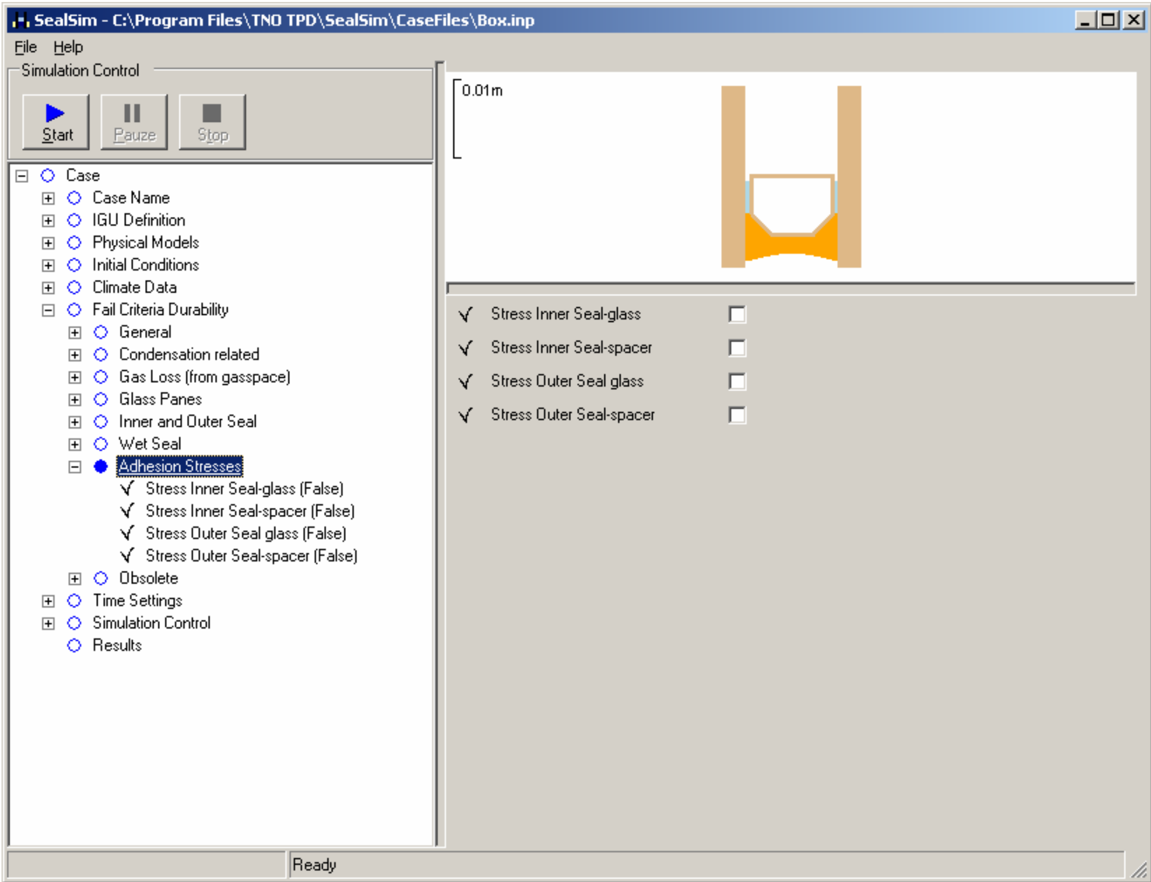


Figure 4.7.1.34 Failure Criteria - Adhesion Stress Selection Screen

The Adhesion Stress Failure sub node is shown in Figure 4.7.1.34. The user does not need to enter failure threshold values for these criteria as they are defined by the properties of the seal interface properties entered in the Interface Properties sub node and the dimensions of the IG unit construction.

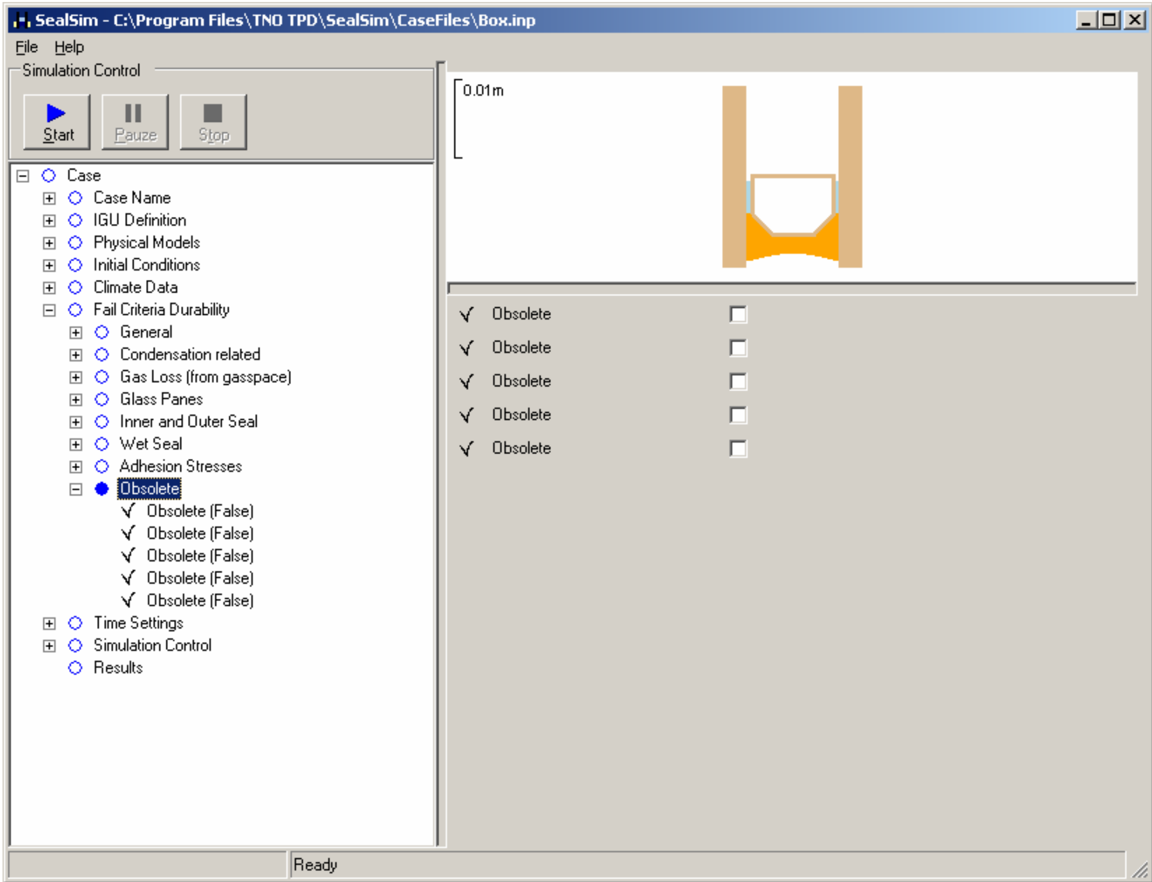


Figure 4.7.1.35 Obsolete Failure Mode Screen

The failure modes listed in the Obsolete sub node (Figure 4.7.1.35) were used for debugging the software during model development and are not used as part of a simulation run.

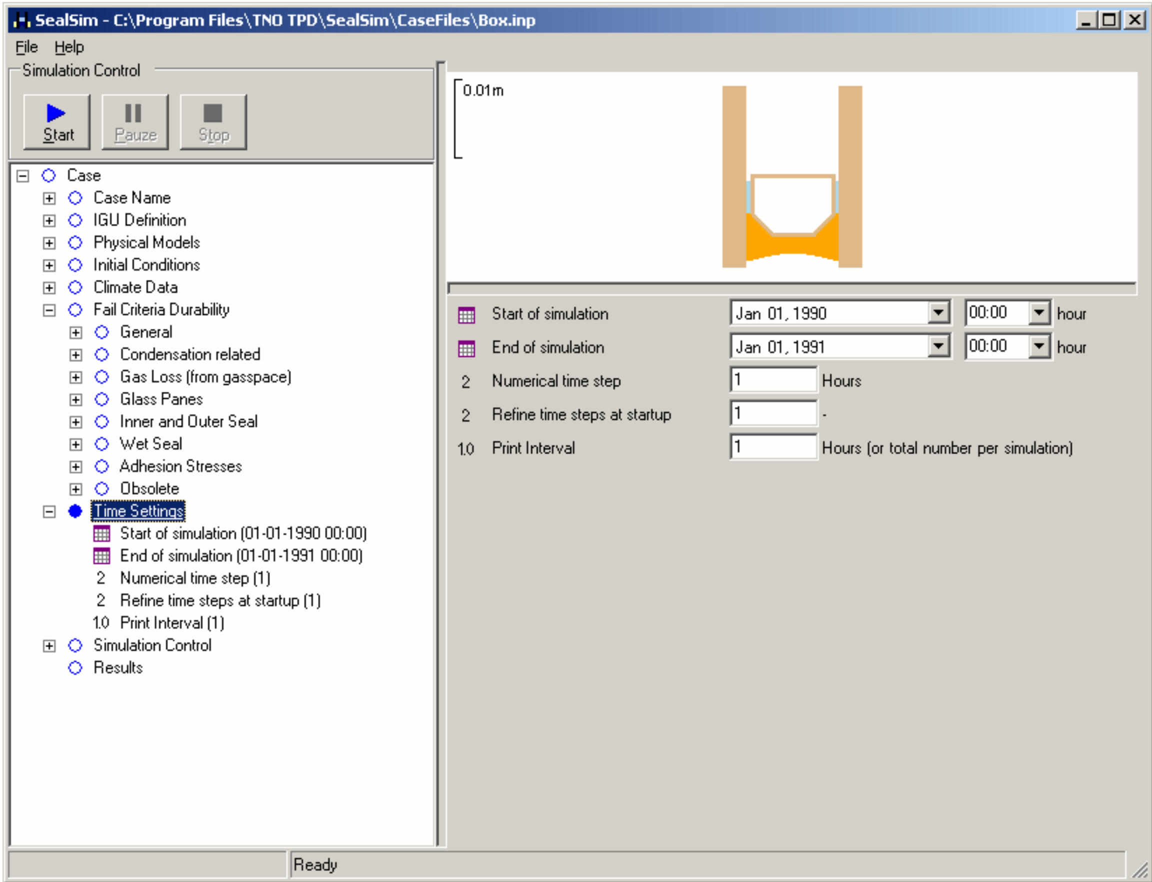


Figure 4.7.1.36 Simulation Time Settings

The Simulation Time Settings Node is shown in Figure 4.7.1.36. The length of each Monte Carlo run in the simulation is entered in this sub node. The length of the time step used for the simulation is entered here as well. The initial simulation step, taking the IG unit from its conditions at manufacturer to the modeled environmental conditions can be so abrupt as to not allow the model to quickly converge. If this occurs, additional time steps can be added with the "refine time steps at startup" field, dividing the transition from the manufactured condition to the simulation conditions into smaller temperature/pressure steps.

The print interval defines the time interval at which the simulation will write information about the simulation to the output files. If a negative number is used, it is interpreted as the total number of times that output will be written during the simulation time period in equal intervals throughout the simulation.

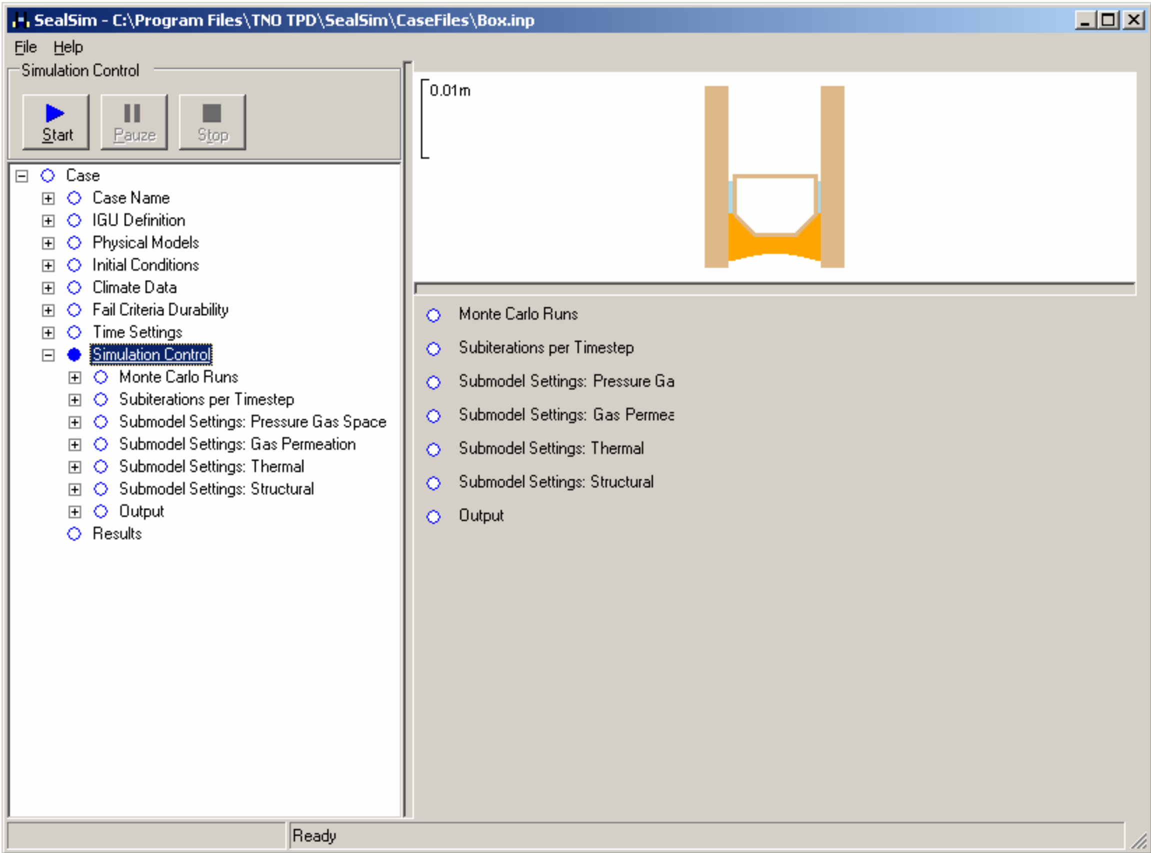


Figure 4.7.1.37 Simulation Control Node – Overview

An overview of the Simulation Control Node is shown in Figure 4.7.1.37. This node contains the modeling parameters used in the simulation including the number of Monte Carlo runs and the number of iterations allowed for the sub-models.

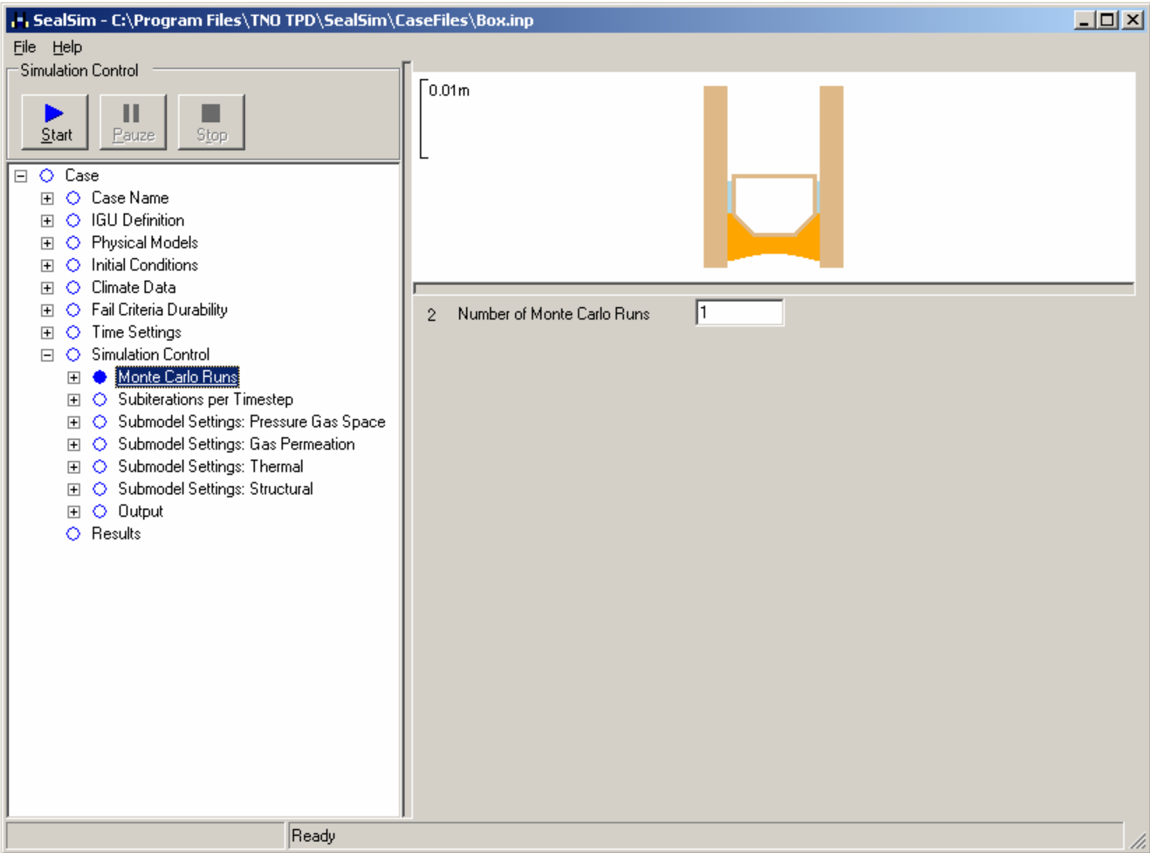


Figure 4.7.1.38 Monte Carlo Runs

The number of Monte Carlo sub node (Figure 4.7.1.38) controls the number of Monte Carlo runs that make-up a simulation. For each Monte Carlo run, the input parameters having probability distributions will be varied. If all of the parameters have fixed values, every Monte Carlo run would give the same result. The simulation checks for such a situation and, if detected, will perform just one Monte Carlo run.

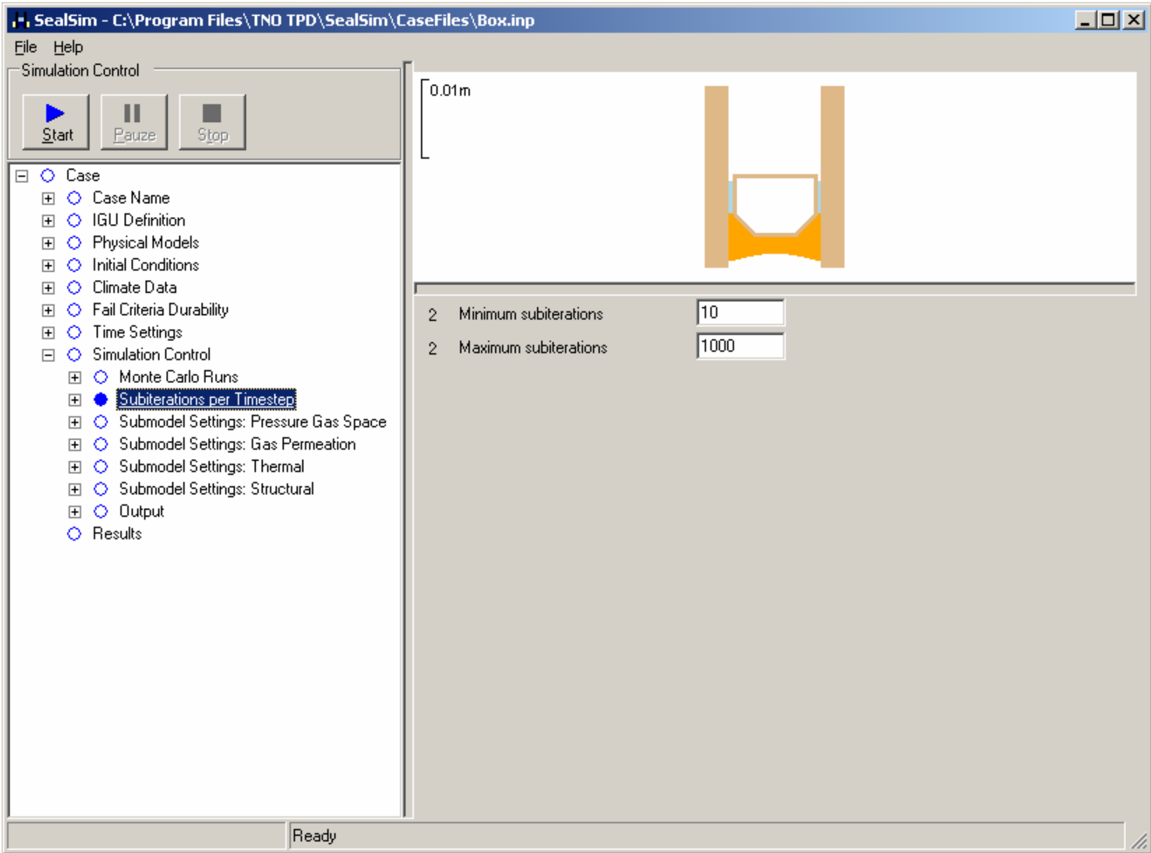


Figure 4.7.1.39 Sub iterations per Time Step Sub node

The Sub-Iteration sub node is shown in Figure 4.7.1.39. In this sub node the minimum and maximum number of iterations made per time step is set. Within each time step, the models are called sequentially.

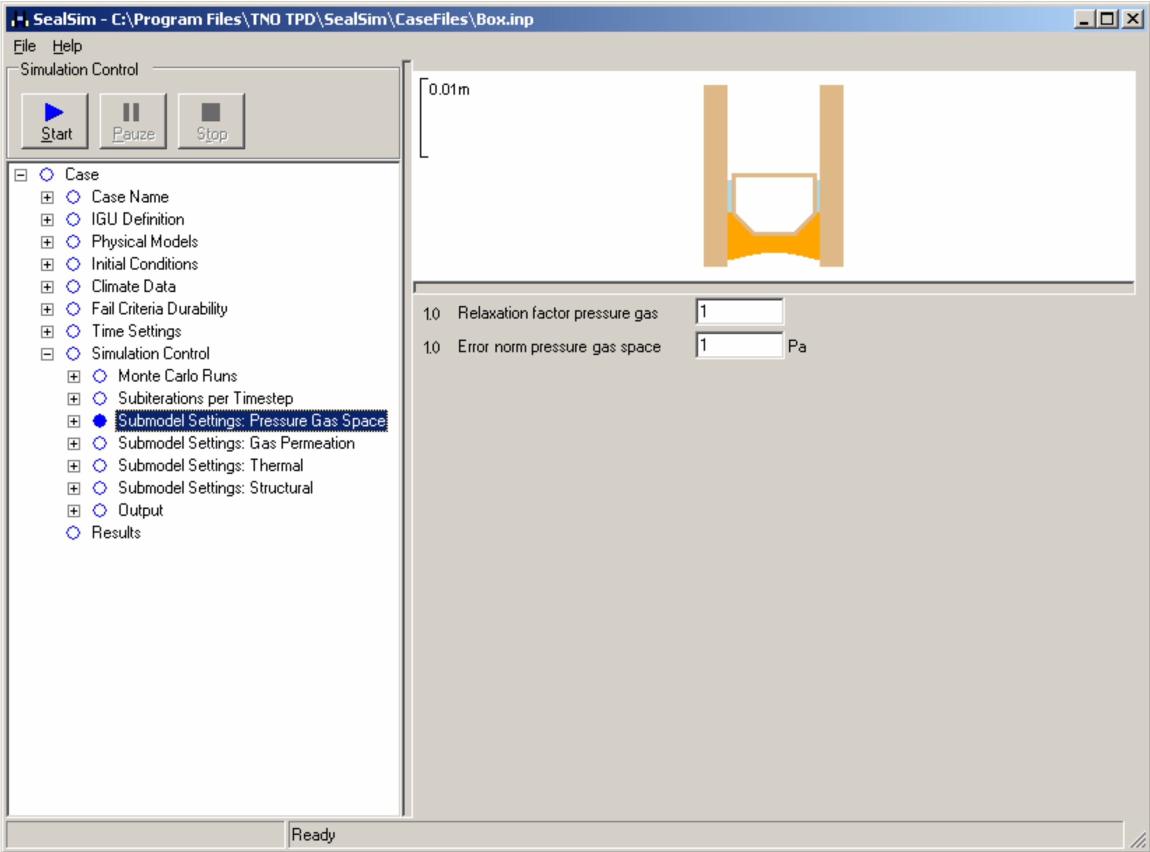


Figure 4.7.1.40 Gas Space Pressure Sub model Settings Screen

The sub model settings for the gas space pressure are shown in Figure 4.7.1.40. A relaxation factor applied during each of the model iterations of the gas-space-pressure model is entered here. And, the residual (error norm) used to determine convergence of the model is entered here.

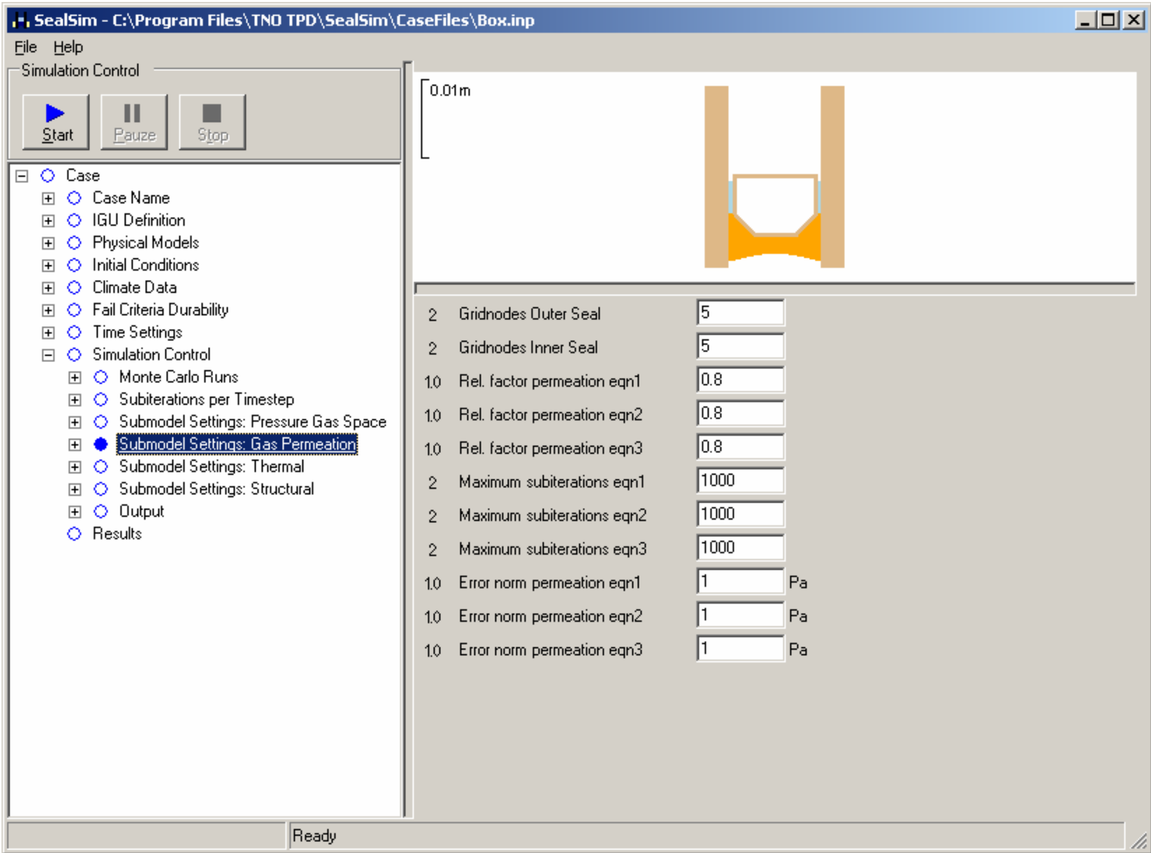


Figure 4.7.1.41 Simulation Control - Gas Permeation Sub model Settings

The Gas Permeation Sub-Model settings are shown in Figure 4.7.1.41. The number of grid nodes used when modeling the inner and outer sealants is entered here. Relaxation factors, maximum number of iterations and "Error norm," the residual value used to determine convergence, for each of the three permeation equations are set here.

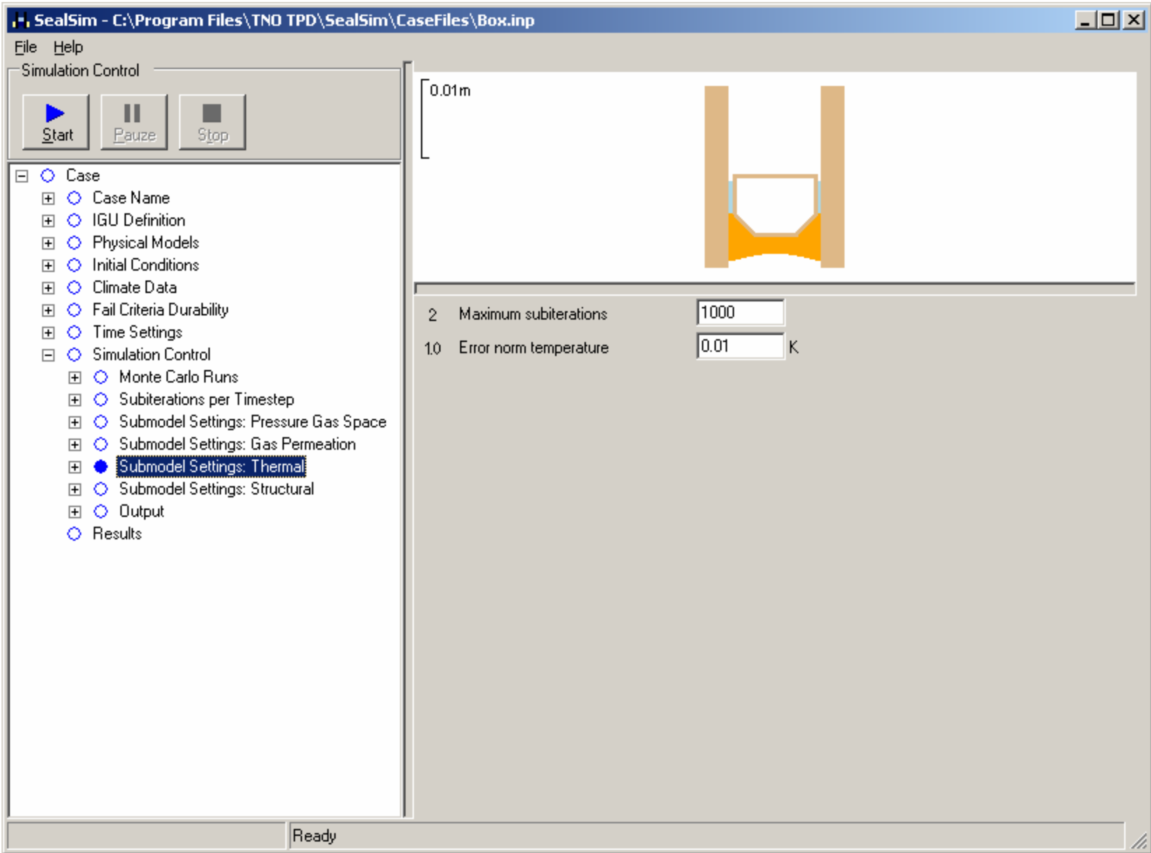


Figure 4.7.1.42 Thermal Sub model Settings Screen

The Thermal Sub model settings are shown in Figure 4.7.1.42. The maximum number of iterations and "Error norm," the residual value used to determine convergence, are entered here.

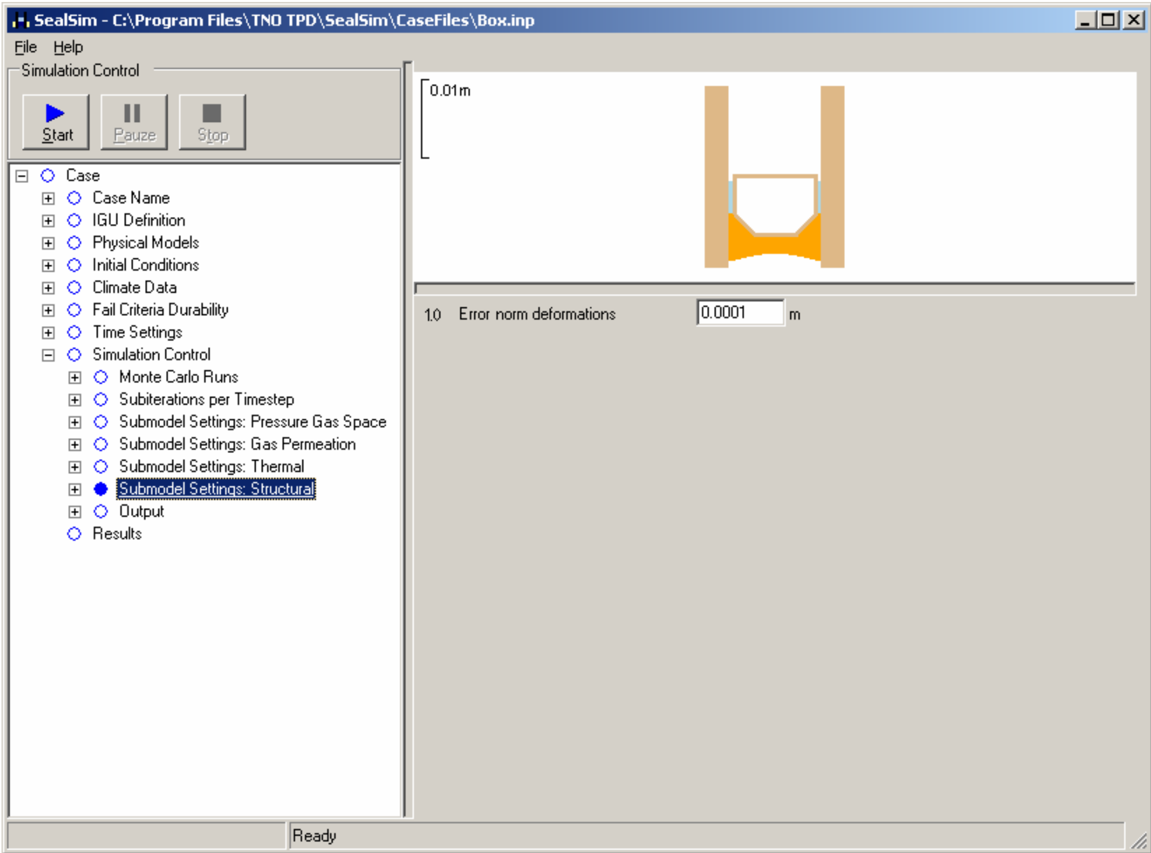


Figure 4.7.1.43 **Structural Sub model Settings Screen**

The Thermal sub model settings are shown in Figure 4.7.1.43. The "Error norm," the residual value used to determine convergence, is entered here.

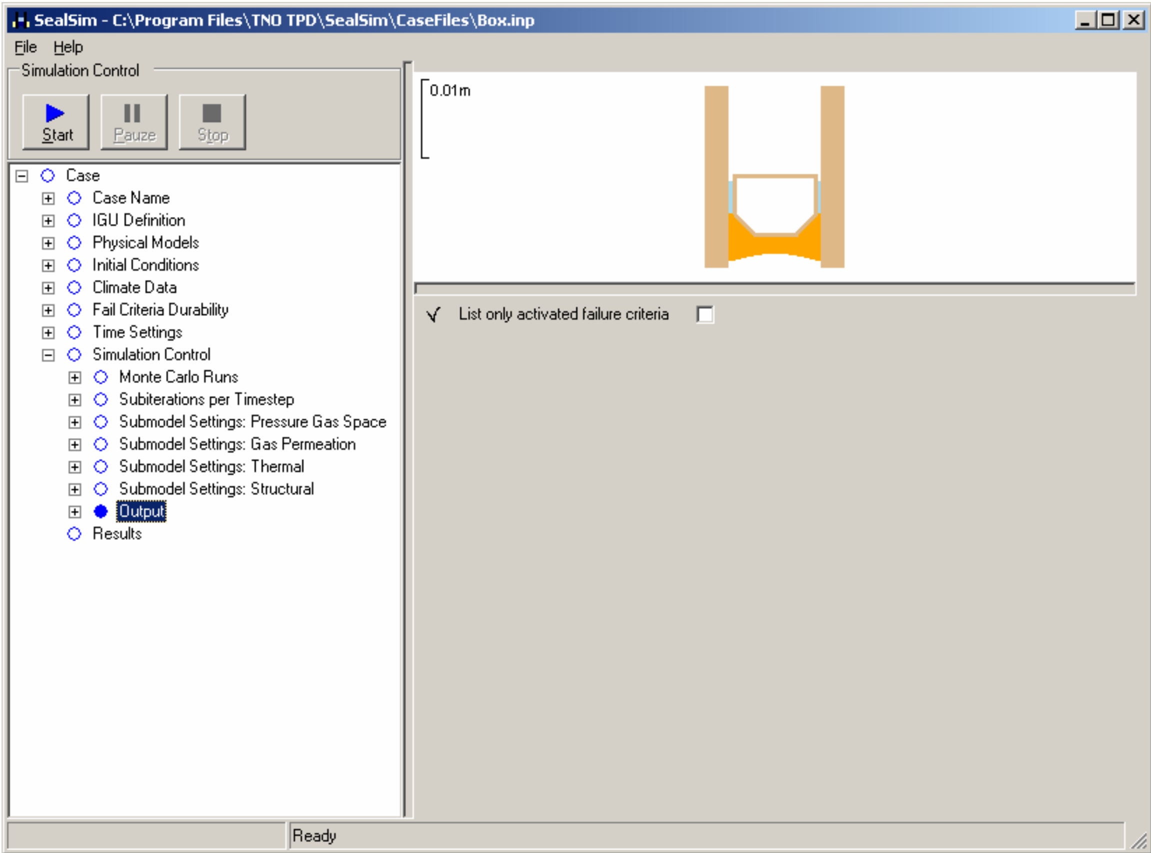


Figure 4.7.1.44 Simulation Control - Output Selection

The Output sub node (Figure 4.7.1.44) determines the number of failure criteria which will be written to the output file. Checking the box will cause the simulation to only write the values of the active criteria to the output file, creating a shorter file. If the box is unchecked, the simulation results for all of the failure criteria will be recorded.

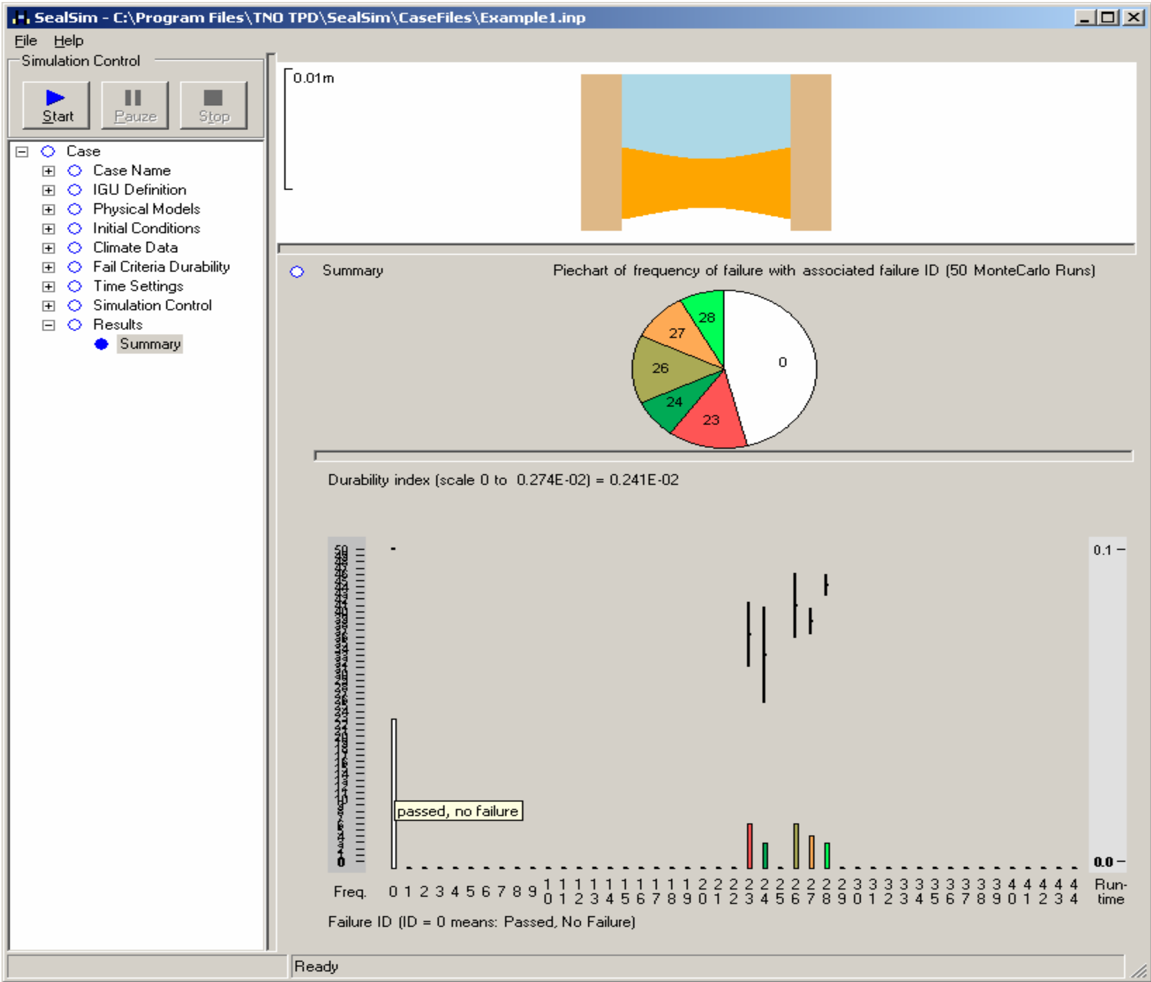


Figure 4.7.1.45 Results Summary Screen

The Results Summary node is shown in Figure 4.7.1.45. In this example, a simulation consisting of 50 Monte Carlo runs was made using the "obsolete" failure modes (created to debug the simulation software). A summary of the simulation results showing the proportion of each of the failure modes encountered during the simulation is presented as a pie chart. The numbers in each section of the pie chart refer to the number code for the failure mode.

Details of the simulation are displayed at the bottom of the Results screen. The left axis indicates the number of Monte Carlo runs that were performed in the simulation. The time to failure is shown on the right axis. The frequency of failure modes are shown in a histogram format. While there is only space available to identify the failure modes in the plot by number (x-axis), a window (such as the “passed, no failure” seen in Figure 4.7.1.45), identifying the failure mode by name appears when holding the cursor in each column in the histogram. The average time to failure for each failure modes is presented as a whisker plot. The mean time to failure for the failure mode is shown with a dash while the standard deviation is used to define the error bars.

In this example, 23 Monte Carlo runs were completed without encountering a failure, Failure Mode 23 occurred 7 times; Failure Mode 24 occurred 4 times; Failure Mode 26 occurred 7 times; Failure Mode 27 occurred 5 times and Failure Mode 28 occurred 4 times. Details of each of the Monte Carlo runs and a tabulation of the frequency of failure and associated standard deviations are found in the simulation’s output file (*.out).

The Results window also shows a “Durability Index” for the simulation. The Durability Index is the mean time to failure for the Monte Carlo runs, based on the simulation of the IG unit behavior over the user defined simulation time period. An IG unit with higher Durability Index is considered to have a longer service life than a unit with a lower Durability Index. If IG units do not fail within the timeframe of the simulation, the Durability Index becomes a conservative estimate of the simulated service life. Since it is unknown to the simulation when the IG units passing the simulation will fail, for the purposes of the Durability Index calculation, the simulation time is used for their service life. The Durability Index can therefore be improved by running the simulation over a longer time period until all of the units fail.

It is important to remember that the Durability Index is based on simulations and is not validated against real life data. At best, the Durability Index can be used to compare different IG unit designs, taking into account the limitations of the physical models, though no guarantee can be given that this is correct. When comparing IG unit designs based on the Durability Index, the comparison is only valid if the simulation time period and all conditions applied are the same for all designs.

To demonstrate the effect of the environment on the permeation of moisture into an IG unit, a simulation using the TPS system was performed. The failure criterion for this simulation was an -18ºC (0ºF) dew point in the IG unit air space. For this demonstration, the material properties of the IG unit were manipulated in such a manner as to allow the IG unit to pass ten years of exposure to one climate and fail in a more humid environment. The results of a single Monte Carlo run in each environment are shown below.

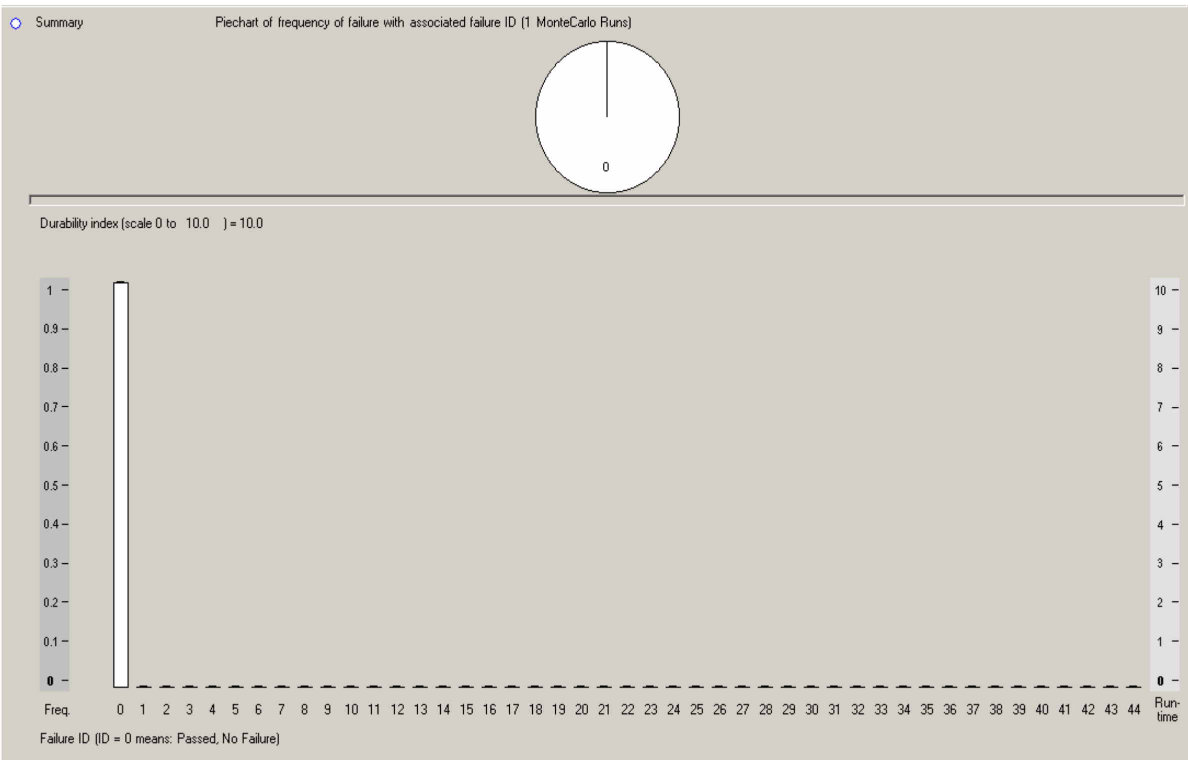


Figure 4.7.1.46 Simulation results with no failures

Figure 4.7.1.46 shows the results for the Monte Carlo run using the Typical Meteorological Year data (TMY2) for Central Park in New York City. In this case, since the unit did not fail within the 10 year run the Durability Index is 10. When this simulation was continued to failure, a Durability Index of at 14.05 was achieved.

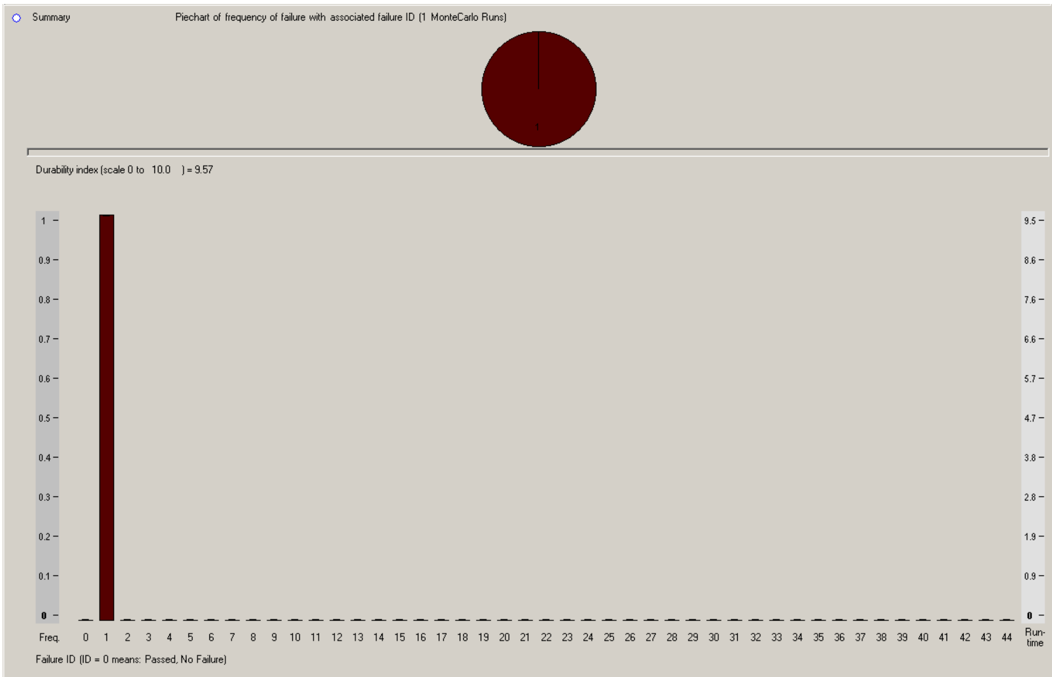


Figure 4.7.1.47 Simulation results with dew point failure

Figure 4.7.1.47 shows the results for the Monte Carlo run using the Typical Meteorological Year data (TMY2) for Miami, Florida. Miami is a higher humidity environment than New York City (severity of 2800 vs. 1300 psi-hours). As would be expected in this environment, the IG unit fails sooner during the Monte Carlo run, yielding a Durability Index of 9.57.

4.7.2 Advancement – Future Considerations and Compliance with Current Tools

Background

Phase I of the IG unit durability knowledge base project was expanded to include computer tool development that can be used by the fenestration industry to predict the durability of IG unit products in a user friendly and consistent manner. The development of this tool is a critical component of the project, because it introduces, for the first time, an industry standard for the prediction of service life and durability. This is the kind of tool that has long been sought by the industry and professionals in the fenestration related field.

The intent of the durability simulation tool is first, to support the IG design activity with several secondary applications identified such as helping to define and support industry guidelines or rating systems which consider the importance of durable IG units. The FMEA was suggested and chosen for development as a design support methodology because fenestration designers can trace defined IG system failures directly to a root-cause failure. As described in the Phase I report, the system failures (failed IG units) have been defined and are generally documented in the field as failures that are recognized and initiate service activity by the user (home or building owner). For example, the owner recognizes moisture or frost on the glass surfaces. This is recognized as a failure and a service call is a likely outcome. During the service or repair activity, the failure will normally be documented at the level it was reported (moisture or condensation on the glass) and possibly the best guess as to why. Further analysis of the unit to absolutely discover the root cause of the failure (cohesive failure for example) is expensive and only rarely undertaken. In the example of a condensation failure (as is true of most failures defined at the customer level of resolution), there are several root cause failures that can initiate a path of failure activity resulting in the recognized condensation failure.

The FMEA analysis and associated event trees will, in a statistical manner as described here, develop the possible failure paths that lead to these overall system failures. In each of the failure nodes represented in the event tree, a failure is defined as stresses exceeding strengths. In the case of a material fracturing or breaking, the stress exceeding the material strength is easily envisioned and understood. A stress exceeding strength in association with permeation can be viewed and modeled in a similar fashion. The property(s) of a sealant designed to stop or control permeation are the strengths of the material in its ability to achieve the designed result. This sealant property, with its variance can be represented by minimums, averages, maximums or a known distribution; the distribution of the material's ability to stop or control permeation, its permeation-rate strength. The force or stress distribution acting against the permeation-rate strength contains the resolved stresses (thermal, mechanical, chemical, etc.) as presented in the first Phase of the project.

The resolved stress distribution is continually changing based on the environmental inputs. In addition, the distributions that represent the material strength properties of interest may also be changing as the material reacts to particular stress inputs. When a degrading material strength eventually interacts with an instance of high stress input, the chances of failure are increased. On the other hand a degrading material stress continually exposed to a set of lower magnitude stress distributions, may not contribute to a detectable failure for some time; until the stress increases, for example. It is obvious that what seems to be a simple comparison of two distributions requires a great deal of continuous supporting calculation and input data.

As the stresses and strengths are compared at the root level, a detected failure distributes an additional set of conditions to the next level of consequence. (In a two seal design, if the outermost seal, the secondary seal, fails, the inner seal or primary seal is exposed to additional moisture. Or if the primary seal fails, the secondary seal may be exposed to argon molecules.) As presented, there are several paths or buckets at the next level in which the root failure will travel. The additional input (stress) from the root failure may or may not accelerate the next level of failure as the stress distribution is adjusted with the new information. This process will continue as the root-cause failure works its way through each level eventually contributing to one of the defined system failures at the target or customer level. In this way, failure data collected in the field can be statistically traced to the most likely (then the second most likely etc.) root cause. A designer can then address the fundamental cause(s) of failure eventually resulting in a more robust, durable product.

As will be explained, the chosen direction for the initial simulation code focuses on the fundamental models and the set(s) of differential equations, coupled and solved simultaneously in a real-time analysis. The relationships and supporting modeling representing the interactions of the failure modes was not included. A set of simplifying assumptions are made and failure criteria are defined at the material or root cause level and up through the system level where the customer detection of failure is also defined as described above. As discussed earlier, each failure can be turned on and off giving some functionality to exposing failures at the root cause level. However, in the current simulation once a failure of interest has been has been detected and is turned on, the simulation ends, the unit failing at that time. This evaluation of root causes is different. As explained above, a root cause failure may not immediately lead to a system or unit failure. Depending on input stresses and material strengths, it may take a lengthy period of time for the root failure to contribute to the full unit failure.

At the system level of failure, condensation on interior surfaces is identified as a failure and can be switched on and root cause failures (say, bulk material property failures) are turned off. In this run, the simulation will continue until all conditions are met for condensation, thus the simulation will calculate through the root cause failure and continue until the conditions for condensation are detected. Examination of intermediate calculations collected throughout the simulation run could reveal several root-cause failures had occurred. The possible dependencies of the failures (the failure path) will not be identified.

The time based simulation models the behavior of the system, detecting failure, as if in real time as opposed to the statistical probability of failure occurrence. With a significant number of well defined runs and analysis of intermediate calculations, possible root cause failures can be identified and direction for improving IG durability can be defined. This first iteration of the simulation code is a strong and immediately useful foundation on which to build. The outcome of this project will result in the development of the first tool of its kind in the service life prediction and durability field. It is also expected that the experience and results from this project that deal primarily with IG durability, will be expanded to the entire field of fenestration products, including frame components.

DELIVERABLES

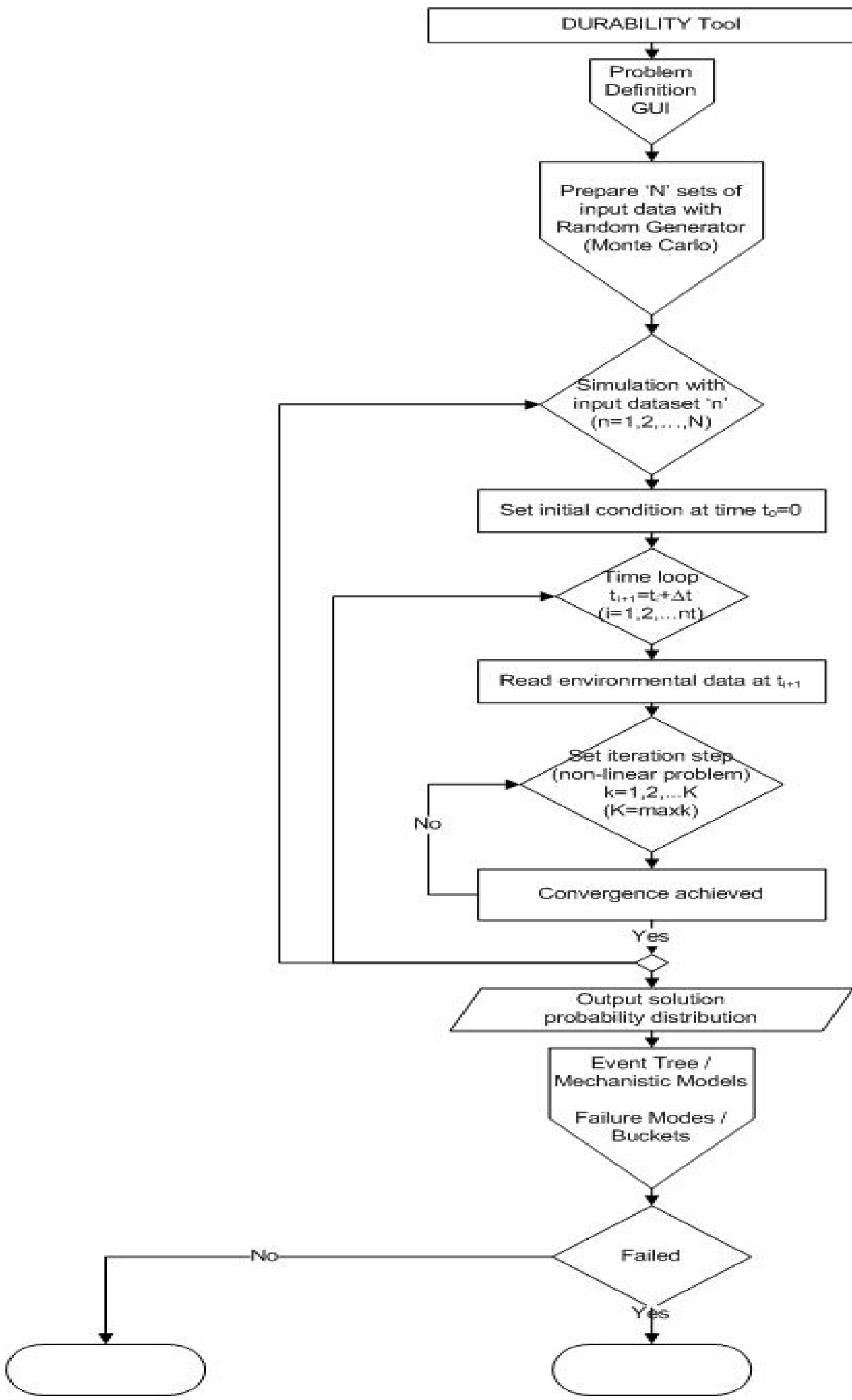
(Important highlights)

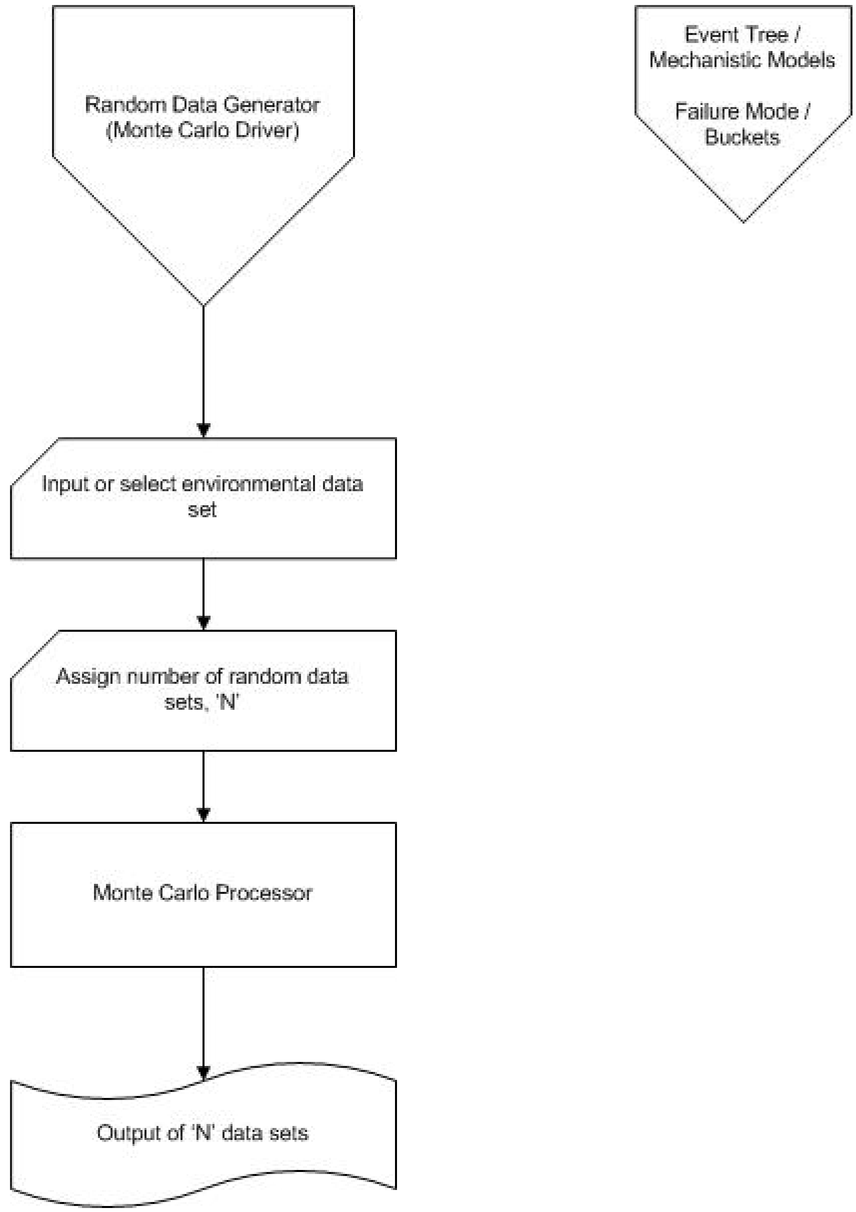
- Computer tool development resulted in the following compatibilities:
    - WINDOW optical and thermal calculations
    - IGDB compatible
    - Standard weather data
    - Database foundation
    - Xml interface
    - Fortran 90 source code
    - Seamless future updates

- SealSim fulfills the promise of being the first usable durability tool for insulating glass products and their application
- The GUI provides an industry standard interface that can be easily expanded
- Weather data modified to include Monte Carlo parameters for random variations and provisions for extending the data sets beyond the one year provided
- New method of real-time simulation was developed during the project
- Devised novel approach of combining real-time simulations with Failure Mode and Effects Analysis (FMEA) and event tree analysis while proposing a future path
- Technical paper written on the novel approach
- Proposed novel approach of simulating accelerated testing conditions and developing durability predictions, suggesting new standards can be developed on this premise

- NFRC, IGMA and AAMA fully engaged in the approach and a consortium of manufacturers and government entities was formed to continue the project
- Developed proposal and submitted to DOE for continued funding

Figure 4.7.2.1 Flow Chart of the Proposed Durability Tool




Random Data Generator
(Monte Carlo Driver)
Event Tree /
Mechanistic Models
Failure Mode /
Buckets
Input or select environmental data set
Assign number of random data sets, 'N'
Monte Carlo Processor
Output of 'N' data sets

Discussion and Possible Directions for Preparing the Translation of 2-D and 3-D Programs into 1-D and 1½ D Programs

Current work on 1 D and 1½ D heat transfer and mass transfer models involves mostly 1-D physical model results (center of glass for thermal and 1-D mass transfer through homogenous slabs, corrected by area weighting – that is face area for mass transfer through the spacer assembly). This approach has been deemed appropriate for this Phase of the project due to a large number of possible configurations and prohibitively expensive running times if full 2-D and 3-D models were incorporated.

It is also a sensible approach to such problems for which almost nothing has existed before and where there are so many possible interactions and unresolved consequences. The following describes;

a) Some suggestions for immediate improvements in this approach, which can easily be implemented in this stage of the project, and

b) Recommendations and directions for future work, which can be either incorporated into a new proposal to DOE or can serve as a general guideline for future work.

Possible Improvements to current models:

In the area of thermal modeling, 1-D heat transfer prediction through the center of the glass is a reasonable estimate of the average temperature that exists on each side of the glazing. This prediction can be successfully used for predicting bulk gas properties in the cavity and are somewhat less reliable for predicting the temperature of the sealant and spacer.

This prediction could be improved by considering effective conductivity of the spacer assembly (see procedure in Example A below) and correlating this value to the center of glass temperature distribution in developing a simple correlation for sealant and spacer assembly temperatures. Absence or presence of solar radiation on the whole exterior surface or certain sections of the IG unit can also be included in a correlation for predicting temperature distribution in a sealant.

In the area of mass diffusion modeling, the effects of the interface between sealant and spacer and the measure of their adhesion can be also correlated to provide correction factors to simple area weighting of surface areas in predicting mass transfer through the spacer assembly.

In the area of stress and strain modeling it is not yet clear how the 1½ D model works, so further comments will be left for after the model has been disseminated.

Future Directions for translations of 2-D and 3-D Models to 1½-D Models

The translation from multi-dimensional models into their reduced form (i.e. 2-D into 1½ D and 3-D into or 2½ D) can be accomplished using two basic approaches;

1) Utilization of numerical methods (brute force approach) to solve a full set of governing equations without simplifications; and

2) Introduction of simplifying assumptions into the governing equations in order to accomplish an analytical solution in a closed form.

A combination of the two approaches may also be appropriate. Depending on the approach, the problem can either be directly incorporated into the durability tool (more appropriate for simplified analytical models) or the results of physical models are mapped (translated) into the analytical model built into the durability tool (appropriate for numerical solution). In its extreme cases, full multi-dimensional numerical models could be incorporated into the durability tool, and while this option would provide almost absolute accuracy, the hurdles to implementation of such a method are so huge that it will take many years for this approach to be viable. However, implementation of numerical simulations in some limited form prepares the model for future full implementation, where the translator is simply replaced by the full numerical model.

Analytical Approach

A general method of 2D to 1D translation of governing equations is obtained by integration in one dimension of the 2D model. If the modeled system is homogeneous in the integrated dimension (i.e. all of the slabs are the same) the translation comes down to simple area weighting. An example of such system is the IG unit, incorporating the TPS spacer. In this case area weighting will give the exact translation for the diffusion equation. In the case of a non-homogeneous system (Box-Spacer System, Example B) simple area weighting translation may be more or less an oversimplification. In the case of a box-spacer system, the area through which the vapor enters the interior of the unit (the area between the box spacer and the glass lites) is much smaller (10-20%) than the total area of the seal. Translation by weighting with the total seal area will clearly overestimate the effects of diffusion in this case. Weighting by the area between the box spacer and the glass lites will, however, underestimate the diffusion effects. The vapor diffuses in the region under the Box-spacer too. In this case the diffusion paths through slabs are not the same, and more importantly, they are not parallel.

The disadvantage of this approach is that there may be some oversimplifying assumptions and sometimes we may not be able to determine if they are oversimplifying or not. The advantage of course is a very fast calculation time, which sometimes may be critical. It may be that the final choice includes a mixture of different approaches as the model develops, so this alternative is presented.

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Numerical Approach:

This approach consists of reading results from numerical simulations of 2-D and 3-D models and then interpreting those results and incorporating them into 1-D models in order to create the1½ D model. The most practical way of incorporating a numerical approach is to use existing 2-D numerical tools, which incorporate some limited 3-D effects (i.e., THERM, WINDOW, etc.), then solve the physical models for a number of boundary conditions. Continuing development would include an interface which interprets these results and prepares input data for use in the durability tool.

For example, the THERM program could be run for a variety of input and boundary conditions and data at strategic locations can be extracted to construct input data for the thermal stress model in the durability tool. These strategic points could be the center of glass, beginning and end of the spacer assembly interface with the glass, interface of IG unit and frame, average temperature of frame components, etc.

Another example, involving diffusion, would be to take sample points in the middle of the sealant, diffusion distribution at the interface with glass and sealant, as well as sealant and spacer, which then can be used together to construct 1-D data for input into the durability tool. In this scenario, the durability tool is largely left intact, with its existing 1-D treatment of physical phenomena and with the improved estimation of 2-D effects for the better definition of the1½ D model.

An alternative path would be to incorporate full 2-D and 2½ D physical models into the durability tool scheme, which would provide less simplifying assumptions. This would require significantly more execution time that could be prohibitively expensive for several years. This approach, however, is the right way to go into the future when the expense of computer running time and resources will not play the same significant role. Some sensible mix of these two approaches seems to be the most effective path.

Example A:

The calculation of k_{eff} (effective conductivity) of the spacer assembly was done according to the following procedure:

Overall U–factor of the individual spacer assembly, shown on Example Figure A-1, was calculated using THERM 5, using the following boundary conditions on the side (i.e., left and right) boundaries:

<u>Exterior surface</u>

NFRC Exterior combined (t = - 0.4 ºF, h_o = 5.283 Btu/h*ft^2*F)

<u>Interior surface</u>

NFRC Default Interior combined (t = 69.8 ºF, h_i = 1.408 Btu/h*ft^2*F)

From the electrical analogy of heat transfer mechanism:

$$R_{tot} = \frac{1}{U} = \frac{1}{h_o} + \frac{L}{k_{eff}} + \frac{1}{h_i} \qquad \text{(A1)}$$

k_{eff} can be determined as:

$$k_{eff} = \frac{L}{R_{tot} - \frac{1}{h_o} - \frac{1}{h_i}} \qquad \text{(A2)}$$

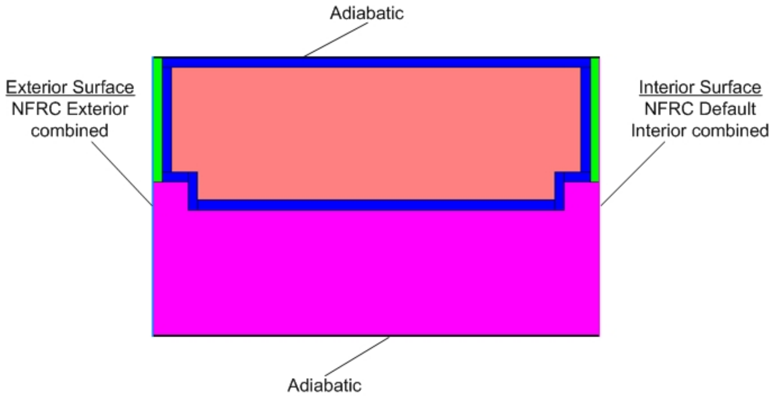
Where:

L = spacer width,

R_{tot} = overall thermal resistance of considered spacer,

h_o = outdoor heat transfer coefficient,

h_i = indoor heat transfer coefficient.



Example Figure A-1

Boundary Conditions and Spacer Configuration Used for k_{eff} Calculation

Example B:

Example of Analytical Solution of Diffusion Equation with a Point Source

In the following derivation an extreme case consisting of non-parallel slabs is solved. The diffusion through the slabs in the following example radiate from a single point. The final result however is surprisingly simple.

Diffusion equation in 2D and 1D

3-D case

Diffusion equation in general 3D case:

$$\frac{\partial \rho}{\partial t} = D(\frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial y^2} + \frac{\partial^2 \rho}{\partial z^2})$$

Where ρ is mass density; D is the diffusion constant. A special case is the steady state (generally established after a certain characteristic relaxation time):

$$0 = D(\frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial y^2} + \frac{\partial^2 \rho}{\partial z^2})$$

2-D case

In 2D the equation becomes:

$$0 = D(\frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial y^2})$$

The solution of the equation depends on the boundary conditions. In the case of single point mass source, the boundary condition can be taken as:

$$\rho(x = 0, y = -d) = \rho_0$$

And

$$\rho(x, y = 0) = 0 .$$

The solution in this case is:

$$\rho(x, y) = \rho_0 (\ln \sqrt{x^2 + (d - y)^2} - \ln \sqrt{x^2 + (d + y)^2})$$

It is clear that:

$$\rho(x, y = 0) = 0$$

There is a problem with the point x=0 y=-d but it can be solved by assuming boundary conditions on a cylinder instead of a point.

1D case;

In 1D case the solution under the given boundary conditions is:

$$\rho(y) = -\rho_0 \frac{y}{d}$$

2D to 1D translation;

In order to translate the 2D to 1D solution we can perform integration over the x coordinate:

$$\rho(y) = \int_{-\infty}^{+\infty} \rho(x, y)dx$$

Knowing that:

$$\int \ln(x^2 + a^2)dx = -2x + 2a \cdot arctg(\frac{x}{a}) + x\ln(x^2 + a^2)$$

We get:

$$\int_{-\infty}^{+\infty} dx(\ln\sqrt{x^2 + (d-y)^2} - \ln\sqrt{x^2 + (d+y)^2}) = -x + x + (d-y)arctg(\frac{x}{d-y}) - (d+y)arctg(\frac{x}{d+y})$$
$$+\frac{x}{2}(\ln(x^2 + (d-y)^2) - \ln(x^2 + (d+y)^2))\Big|_{-\infty}^{+\infty}$$

Since the first two and the last two factors cancel out and $arctg(\pm\infty) = \pm\frac{\pi}{2}$ we get:

$$\int_{-\infty}^{+\infty} dx(\ln\sqrt{x^2 + (d-y)^2} - \ln\sqrt{x^2 + (d+y)^2}) = -2y\pi$$

The fact that we can obtain the form of the stationary solution of the 1D diffusion equation (linear function) just by integrating the stationary solution of the 2D diffusion equation for the given boundary conditions suggests that the translation of the problem from 2D to 1D in a non-homogeneous geometry can be as simple as integrating over one of the coordinates. The solution may be as simple as the following relation between the outside density for the 1D and 2D case:

$$\rho_0^{1D} = (2\pi \cdot d)\rho_0^{2D}$$

Clearly, a case of more complex geometry will result in a different factor. However it is important to note, that for each geometry, we can define a constant factor for translation, no matter how complex the geometry. This factor can be obtained either by analytical or numerical integration of the 2D diffusion equation.

Future Directions in Improving the Prediction of Failure Modes

In the Insulating Glass Knowledge Base project, two general concepts of systems simulations have been considered so far:

1. Simulation model based on event tree diagrams (FEMA)
2. Real-time calculation procedures

Event Tree Diagrams

The Event Tree (FEMA) diagrams method was outlined in the Phase I Final Report (Appendix 1). In the Event Tree approach, the problem is divided into many independent failure modes connected through the mechanistic models. Examples of failure modes are: sealant adhesive failure, desiccant saturation, etc. The failure modes of the IG unit systems were identified and defined by the Failure Modes and Effects Analysis (FMEA) as explained in sections 3 and 4 of the Phase I Final Report.

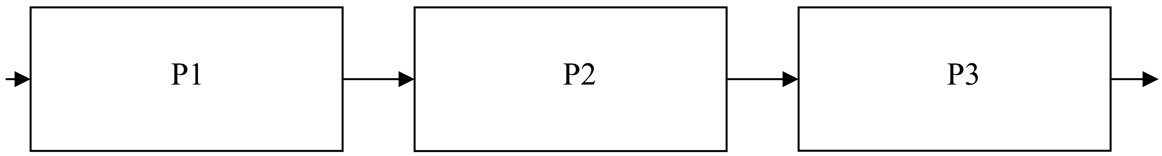
By considering different failure modes, the system is divided into less complex units. Each unit can be modeled by a physical model. The environmental stress is given by a stochastic model based on a climate database. In each failure mode the environmental stress is translated into material stress according to a physical model. On the other hand, the material properties are given by a statistical model based on a materials properties database. After the solution of the physical model, a probability distribution for failure to occur in a given mode is obtained. The modes of failure are organized into event tree diagrams. Relationships of cause and consequence are defined between the different modes. These relationships form a network of connected failure modes. This network of modes is the event tree diagram. In the Phase I Final Report, example event tree diagrams were outlined for each class of IG unit. An example of an event tree diagram is given in Figures Example C 1 and 2 below.

The objective of the event tree simulation is to calculate the probability of failure of the entire system. Also, other stochastic characteristics can be calculated, such as mean first passage time (the average service life of the system), etc (Singh and Billington, 1977).

If the event tree is simple and linear as in Figure Example C 1, the probability for failure can be easily calculated (P=P1*P2*P3). Complex networks (see Figure Example C 2) however cannot be solved exactly (i.e., closed form solution). The only way to calculate the probability of failure for complex systems is to perform Monte Carlo simulations.

In a typical Monte Carlo simulation, a single path of events will occur. At each failure mode-block a random event will occur according to a probability distribution. Depending on the outcome at a given block, the flow of events can take several directions to several following failure mode blocks. For each Monte Carlo run only one path will be taken. After a large number of repeated Monte Carlo runs (for the same initial conditions) a set of paths will be sampled. Given the set of paths, it is easy to determine the most probable path of events, mean first passage time, etc. It is clear that in this case the entire system is not simulated in real time. The average lifetime is determined from the probability of failure.

The differential equations of the physical models are solved in a defined order to obtain the probability distribution for failure for each mode. In this way, the simultaneous solving of the differential equations is avoided. The system is separated into simple units connected into a complex network of events.



P=P1 xP2 x P3

Figure Example C 1 Simple system that can be solved exactly

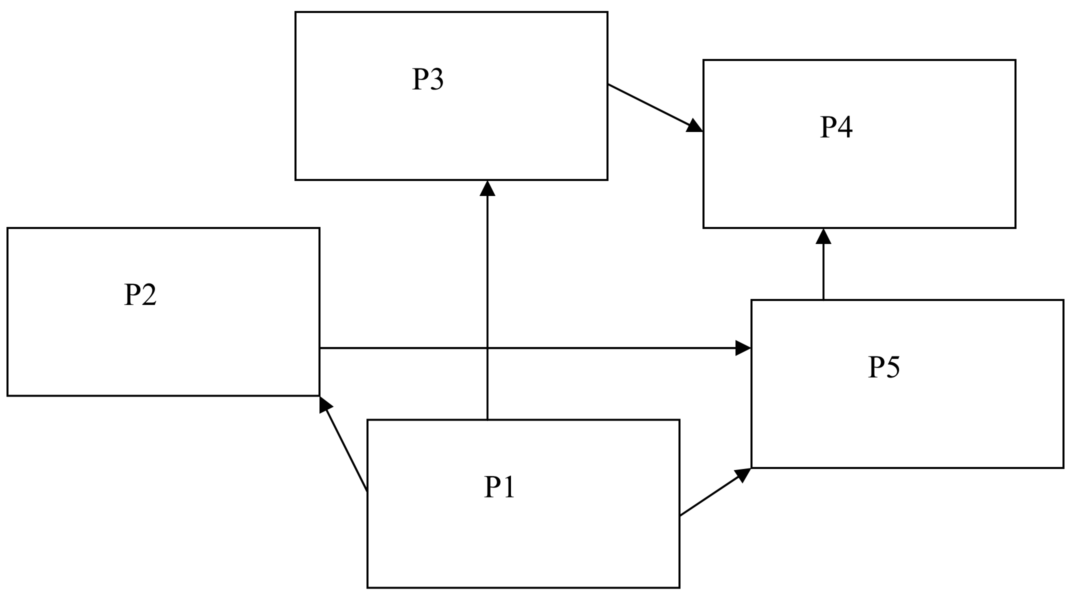


Figure Example C 2 Complex system that can not be solved exactly

This method has advantages of being less resource consuming, and therefore faster. It also has an elegant structure and a simple appearance. The disadvantage of this methodology is that the interactions between different models and failure modes need to be precisely defined and failure paths clearly identified. This is not a trivial task and for complex systems like a window, it would require a significant research effort to develop these relationships and interactions. Also, precise event trees would need to be developed so that coding of the simulation tool can be accomplished. This effort was not conducted as a part of the Phase I project, and instead only the concept and outline of the methodology was developed.

Real-Time Calculations

In this approach the complexity of the system is captured by a model involving simultaneous solving of many differential equations or sets of differential equations, acting simultaneously on the system. (i.e., one physical phenomenon that may cause failure and has an associated failure mode will affect or will be affected by other physical phenomena to a larger or smaller degree, depending on their coupling).

Each equation is given by a physical model (transport of heat, transport of mass, etc.) and their coupling is established through the independent variables present in more than one set of equations (e.g., temperature, pressure, etc.). The system of differential equations is solved in real time. This is a realistic simulation of the actual physical behavior of the system in real time.

After a certain time, the system may fail (according to a definition of failure) and the simulation will be stopped. This simulation procedure will be repeated for many, randomly chosen initial conditions and material properties, both given by stochastic models. Initial conditions and material properties are not fixed and they will vary based on the prescribed set of mean values and possible departures from those mean values – (e.g., tolerances (variances) of material properties). After many simulations are performed for a sufficiently long time period (e.g., 30, or 50 years) a set of times to failure will be generated. In these simulations it is necessary to consider a long enough time to be able to capture failure (e.g., if the unit is going to fail after 22 years, running the simulation for 20 years, or for 10 years will not tell us when the unit is going to fail, therefore we would not have enough information to make any conclusions about the durability and service life of the unit.)

Based on all of the times-to-failure that we calculate in this way, mean service life of the product could be obtained.

Solving simultaneously a full set of differential equations in 2-D or 3-D for a system as complex as an IG unit can be difficult to perform and it is highly demanding in terms of computer resources.

It should be noted that the simultaneous set of equations would need to be solved for N sets of random material properties that are determined from the mean and tolerances set through input data and:

Some statistical distribution of these properties within those tolerances,
Performed for a sufficiently long period of time,

Together, this then would enable a determination of time to failure of the IG unit.

In order to reduce running time and overall complexity, which is likely to be prohibitively expensive at this point in time, a complex system case is described by a simplified model (e.g. 1-D and 1-½D model instead of full 2-D or 3-D simulation). The complexity of the system is therefore reduced and run times for the simulation will likely now be acceptable.

The service life of the system is obtained after averaging over a large enough number of simulation runs. Each simulation run is started with different, random initial conditions. The run lasts until the system fails. The time until failure (service life) is recorded for each run. A measure of durability in this case can be obtained by taking the average of the recorded service lives.

The advantage of real-time simulations is in the fact that coupling and interactions between different physical models falls out naturally from the interactions between equations describing different physical models. No special relationships need to be defined. The disadvantage of real-time simulations approach is in the need to solve simultaneous sets of equations for the entire system and for a large number of initial conditions each time. This is very resource intensive and not very efficient.

In this project, real-time simulations were selected as a method of choice because the amount of work and effort needed in defining relationships between each mode of failure in event tree and development of specific and complete event tree far exceeds allocated budget and available resources. It is, however, feasible to extend the existing real-time approach and to develop event-tree methodology in the future continuation of this project, which would also allow for the utilization of more sophisticated physical models as well (i.e., use of 2-D numerical tools instead of 1½-D models.)

Future Integration of the Two Methods

Both methods described above can deliver the same measure of product durability; the average service life of a system. There is a crucial difference, though, in the method of obtaining the average service life. In the event tree diagram, the time measure is obtained from a probabilistic method. The system is not simulated in real time. Instead each of the failure modes is solved and a probability of failure for each mode is defined. The system is modeled by a network of interconnected failure modes that can be solved by Monte Carlo sampling. The service life of the system is derived from the calculated probability of failure of the system.

A way to integrate these two methods is to perform real-time simulations for each of the failure modes. The interaction between the individual failure modes will need to be defined externally through the use of mechanistic models, which would be based on both measurement and simulation of the complete systems. These real-time simulations will provide the probability of failure in each mode. After the real-time simulations are finished for all failure modes, those failure modes can be organized into an event tree diagram, which can be solved by a Monte Carlo method. This approach was outlined in a flow chart "Durability Flow Chart .pdf" from July 2003 by Charlie Curcija and presented above, Figure 4.7.2.1.

It is clear that in each block of the event tree diagram a probability distribution for failure must be defined. This probability distribution is obtained by multiplication of the probability distribution of the environmental stress and the probability distribution of the maximum allowable material stress. The probability distribution of the environmental stress will be obtained by a time series (real time) simulation of the system. This real time simulation will incorporate all of the elements of the system (in the way currently considered as the simulation of the entire system).

The material properties in this stage however will be fixed and no failure will be considered. In this way we can construct a model to translate the environmental conditions (given by a time series of a typical climate year) into a stress probability distribution. This real time simulation could be done by any component IG unit manufacturer, or some other chosen simulator. The advantage of this approach is that this real time simulation needs to be done only once. The translation function would be part of the final program. The probability distribution of the maximum allowable stress will also be obtained by the manufacturer of the material, either by a single set of simulations or determined by measurements. It seems feasible for a manufacturer to supply, for example, the probability distributions of a sealant cohesive failure for several IG unit classes at different climate conditions.

The advantage of the methodology described above is in the separation of the two methods of simulations:

> The computationally expensive real time simulations are performed by either the authors of the program or a manufacturer of an IG unit, component or material. These real-time simulations are performed only once and the resulting probability distributions are incorporated into the failure modes of the event tree diagram.

The relatively computationally inexpensive Monte Carlo simulations of the event tree diagram representing the entire system are performed by the end user of the program. In this way the user will have more flexibility in designing the system, component or material; comparing the durability of two or more designs and deciding to use an optimal IG design, component and material.

In is important to notice that the real time simulations done by many of the manufacturers will concentrate on a single aspect/component of the system. It is important therefore that the real time simulations tools are designed with this fact in mind. The manufacturer should be able to include only the targeted component and exclude all other possibilities of failure. The real time simulation therefore should have the option of switching on and off different failure criteria. Also, the real time simulation tool should provide a translation function from the environmental conditions to materials stress. Constructing the translation function is done by running the case with all failure criteria switched off. The real time simulation should run until a sufficient amount of stress data from the systems regular (non-failed) behavior is collected.

Summary of the Extension of the Current Methodology:

The current method of simulation in the durability tool simulates the entire system at once in a real time simulation by solving a simplified 1D (or 1½ D) model of the IG unit. Future development in the area of physical models should be focused on a more realistic 2-D or 3-D model. The system however is so complex that simulating the entire system at once by solving the 3-D equations or even 2-D equation seems unreasonable.

- Future development should concentrate on the Failure Modes and Effects Analysis, as outlined in the Phase I Final Report.

- Event tree diagrams should be defined in a precise way, following the outlines given in the Phase I Final Report.

- The simulation methods could be separated into parts to be done by manufacturers (real-time simulations) and parts to be done by the user (Monte Carlo event tree simulations).

- Thermal Model Advancements

  - Estimation of seal temperatures
  - Conduction through the sash
  - Solar absorption
  - Inclusion of diffuse radiation

Other Considerations:

Process and Quality Related Factors like cleanliness of the glass and other surfaces, dust in the production area, use of gloves in handling glass, storage temperature, etc. can affect IG durability.

Process and Assembly
(Inclusion of process and assembly variability into the model)

Processes that are used in the assembly of an IG unit have a tolerance within which they successfully operate. For parameters critical to the service life performance of an IG unit, variations of such a parameter will change the service life of the IG unit. Consider a polyisobutlyene sealant (PIB), commonly used as a primary sealant of the IG unit, because of the low rate at which gases (including water vapor) move through PIB. The amount of material diffusing in and out of the sealant depends on the properties of the sealant as well as the dimensions of the diffusion path. For an IG unit this will be the length of the pathway as well as the width (IG unit circumference) and height (sealant thickness). Thus, a controlled process application of a sealant onto a spacer is an important factor for robust IG durability.

Recommended variable-process considerations for inclusion in the durability simulation are:

- Sealant Adhesion affected
    - Glass cleanliness (residual detergent, fingerprints)
    - Oils on spacer
    - Handling of sealant after application onto spacer
- Temperature of sealant during pressing
- Primary sealant pressing pressure

Process Characterization

The IG unit assembly process establishes many of the factors that will determine the service life of the IG unit. In order to understand how the process would affect that service life, the process must be characterized. This information can then be used by the user in the Durability Design Tool to develop the IG unit system that will be tested. There are a number of variables used by the simulation that are allowed to vary within prescribed limits, describing the tolerances that are inherent to the manufacturing process.

Define Durability and Universally Accepted Measures of Durability

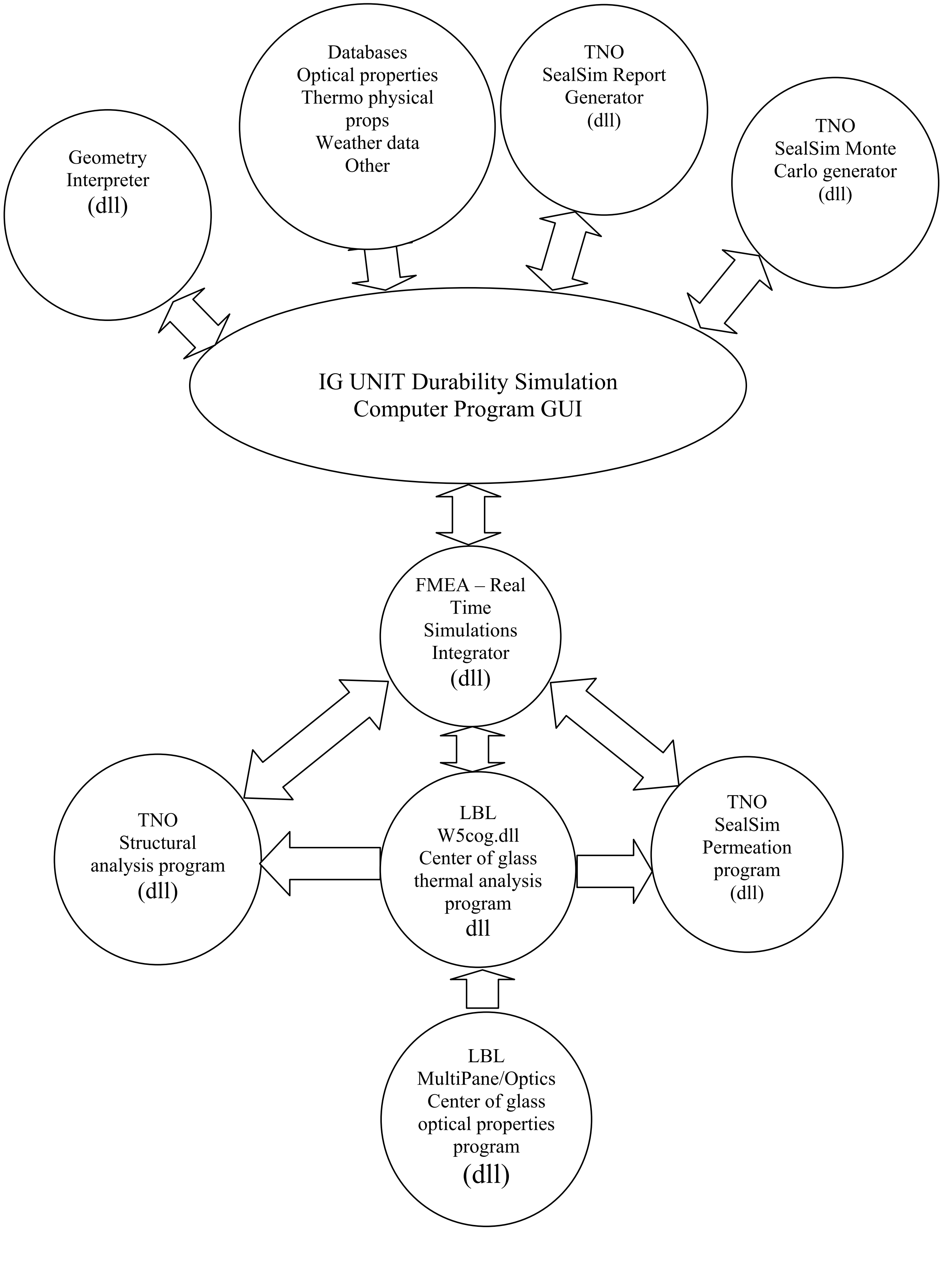
Two IG units should be discriminated as more or less durable for a given geographic area by a universal parameter/measure of durability. A measure of average service life of the system seems like a reasonable unit. The problem is that one can define averages in several different ways. In the case of real time simulations the average can be taken over several runs. In the Monte Carlo method the service life can be defined as the inverse of the probability of failure. These two measures are not necessarily the same.

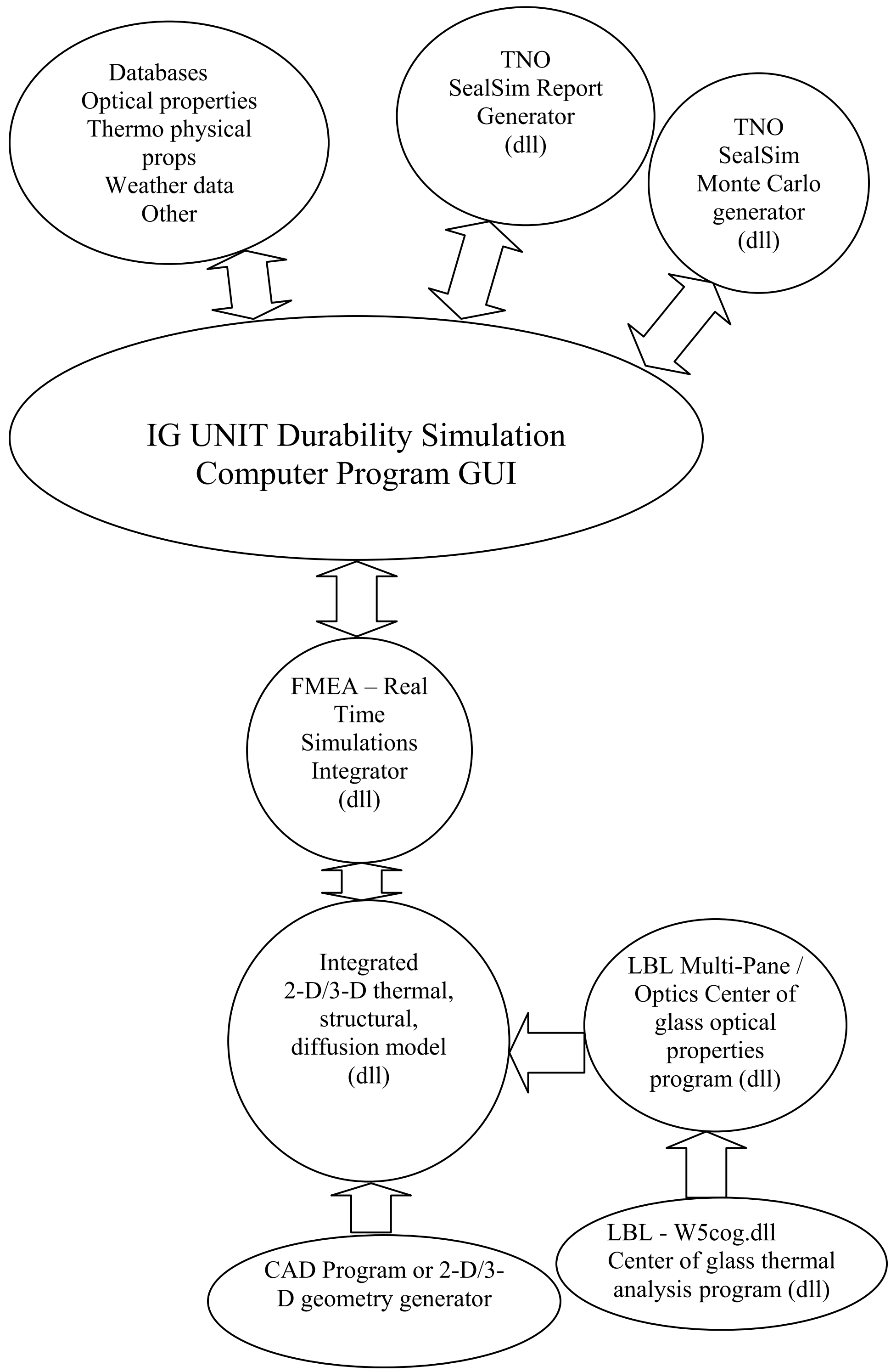
Simulate Accelerated Testing Conditions and use these results in predicting the service life of products. Validate the simulation results using testing and develop reasonable validation criteria. This could dramatically reduce run time, since service life of the system is predicted from the behavior of the product under the extreme environmental conditions, including rapid cycling, for a much shorter period of time than under real conditions.

As a first step, using the same accelerated testing criteria, the service life of the product can be determined from a few months worth of "exposure" to extreme environmental conditions. This approach will support the development of a rating procedure of durability of fenestration products. Also, it would provide a relatively inexpensive means of performance evaluation under accelerated aging conditions.

Continue to Advance and Implement Model Satisfaction, by developing 2-D physical models and providing extension for the 2½-D models. Utilizing and leveraging existing 2-D tools and 3-D corrections developed for fenestration performance assessment over the last 20 years (i.e., THERM, SPACER, WINDOW, etc.) as well as the tools under the development (i.e., FENSIZE, UNIFEN, etc.). Develop the next generation of computer models that would be utilized in the development of the extended durability approach as described in first three points.

Figures 4.7.2.2 and 4.7.2.3 Proposed Flow Charts, Future Development




Databases
Optical properties
Thermo physical
props
Weather data
Other
TNO
SealSim Report
Generator
(dll)
TNO
SealSim
Monte Carlo
generator
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IG UNIT Durability Simulation
Computer Program GUI
FMEA – Real
Time
Simulations
Integrator
(dll)
Integrated
2-D/3-D thermal,
structural,
diffusion model
(dll)
LBL Multi-Pane /
Optics Center of
glass optical
properties
program (dll)
CAD Program or 2-D/3-
D geometry generator
LBL - W5cog.dll
Center of glass thermal
analysis program (dll)

4.8 The Durability Simulation as a Design Guide Tool

As discussed earlier, a primary use of the IG unit durability simulation tool is to help guide the IG design process. The simulation will not provide all the necessary information for a designer to succeed in designing a successful IG unit. The envisioned, developed tool will provide guidance in making decisions that will meet the existing and changing expectations of IG system durability. As is well known, the successful design and implementation of any product is more than its durability, reliability, materials, etc. Thus, the IG designer must consider many requirements which must meet supply chain needs, customer needs, business needs, etc. A successful design process will continue to break all the requirements down to a level in which each requirement is considered in each design decision. Much of the process is based in intuitiveness and experience and with the speed of change in technology, business, information, etc., there is no replacement for intuitiveness and experience.

Yet, more and more information is being collected and used to guide the product development process. Each designer requires as much input information as possible to hit the bulls-eye; creating, engineering and developing a successful product. If required information is missing, the designer must fill in the blanks as best they can and move ahead. With the application of today's business tools, designers can get a great deal of information describing a product's requirements from the customer's perspective (usage, size, color, price, availability, etc.), the business perspective (cost, supply, manufacturing, distribution, liability, etc.) and the list goes on. Whether done in an intuitive manner or a formal process, this information is prioritized and positioned for the first, and possibly the most important task of the process. This is the task of describing all the requirements in terms which are tangible, workable, measurable, etc. things or activities which must occur at some point to succeed. This means describing color, for example, in terms of the actual material and process that will be used to achieve the desired result and the metrics that will be used to verify the result. Or, describing a seal expectation (like an IG seal) with the material, process and metrics to verify success. This new, technical description of the product is the product and engineering specification. It is the recipe, including all the ingredients, processes and expected outcome, for producing the product. These specifications are living documents that should be continually revised throughout a product's life cycle to reflect new opportunities in design, materials, application, process, etc. which advance any element of the product or business.

Armed with the information on customer or business expectations, etc., the designing and engineering process must build the specifications by applying the environmental constraints to the expectations. For an IG unit, this involves considering all the possible issues that can affect, say, a clarity expectation, from the raw material through the manufacturing processes and the period of time the IG is in service. Each and every decision must keep the clarity expectation in mind. Elements (materials, processes, etc.) that enhance or assure good clarity will be embraced; elements that negatively effect clarity will be designed or engineered out of the product or process. This is true of all expectations being considered in the design process, and this becomes a balancing act as each of the product expectations are combined with the business expectations and additional considerations.

The current IG design tool focuses on the durability aspects of the IG system. From the design point of view the process of using the tool effectively results in supporting information that is combined with additional constraints so that together the best choices are made to achieve an expected IG durability. The input into the simulation tool is the first, best guess representing the product. In other words, the designer enters the IG product and engineering specifications into the simulation program. The designer also enters the expected environmental constraints in the program. The environmental constraints are all the elements the product, from raw material and manufacturing variance to the forces acting on the IG throughout its intended life, must successfully endure. It is obvious that this is a great deal of information and data to consider.

The result of the simulation may point in a direction of a new material development or change in overall design or a process design issue as examples of required change. The IG designer considers the new input, adjusts the IG specification if required and runs another simulation. Thus, the tool is part of an iterating process to guide decisions which affect the durability aspect of the product.

The current version of the tool uses simplifying assumptions at several different levels and requires validation. The output can be useful in making design comparisons at a high level and getting a feel for variance in manufacturing, material properties, etc. In addition, the program can be useful in beginning to understand the type and magnitude of stress which the IG system designer must consider in the design process.

4.9 The Need for Data Collection, Model Validation

The modeling effort undertaken for this project has been state of the art and effective in demonstrating the potential use of engineering tools to understand the durability of IG units and building envelopes in general. As techniques for modeling durability of IG units in actual window applications improve, there is a need for understanding what the models mean in the real world. In other words, we must understand if the models accurately represent what is going on in the real world. This process validates the model or program and it becomes useful and trusted as a tool. For the current simulation and future durability models to be useful, data collection and statistical validation is necessary. Although there are several different levels of validation required, the validation of field failures and causes is of most importance. This validation will require the combination of manufacturing data together with the actual field exposure data. There are two obvious ways to collect the data:

1) Set up a ten, twenty, or more year study designed to collect the data for validation.
2) Through a designed process, request contributing data from the industry to be used for model validation. (This continues to be the recommendation and direction of the project.)

4.9.1 The Initial Condition Data, IG Manufacturing - Design, Processes and Quality

Throughout the project, the team has recognized the need for the fundamental understanding of individual manufacturer's process and materials variability. In today's manufacturing world it is generally recognized that reduced variability will lead to fewer field failures.

There are many available references for creating data and knowledge around variability in the manufacturing process laid out in quality control books. Many quality oriented systems recognize a quality management system such as ISO 9000 as a method for documenting critical inputs and outputs to achieve a final product manufactured to specification.

4.9.2 Field Service Data

The key to correlating the current durability model to "real" product durability lies in the historical product data (field data) documented in terms of actionable service failures in the eyes of the consumer. In addition, the field data will help in our understanding of the effect of new and different failure causes as designs change in the future. The power of the engineering design tool under development is that new designs that push the limits can more easily be introduced with a basic understanding of the fundamentals and how they relate to durability expectations.

The design and engineering tool must first be correlated to historical field service data. This historical IG durability or failure data seems to be somewhat elusive as the industry recognizes its sensitivity in the market place. It must also be recognized that the many manufacturers may not hear about their product failures. There are of course a variety of reasons for this. Studies in fact have shown as little as 10% of true failures are reported.

"It is generally accepted that failure rates are higher than actual reported failures. It might be expected, in the building industry warranty claims make up 10-30% of actual failures. While it would be hard to differentiate between customers not finding/noticing the failure and bothered customers not complaining about the failure, the studies have shown these phenomena to be true.[1]

"One study found that 70 percent of unsatisfied customers do not bother to complain because they don't know whom or how to call, or they don't think the company will respond… Another study found even grimmer numbers. The authors concluded that the average business does not hear from 95 percent of customers that are dissatisfied.[1]

[1]Source: Management Review, 03/01/1997, Thank heavens for complainers, (good for business), Oren Harari

4.9.3 Insulating Glass Industry Quality Management System and Field Service Data Request

Attached is a draft of, or suggested form of, a request which was presented to the Insulating Glass Manufacturer Alliance (IGMA) to solicit useful estimates of variability in the manufacturing systems from the IG industry (the total value chain). This survey is intended to be a quality baseline. In addition to this request, data from certification testing could be extremely useful in understanding variability in product and validating the simulation model.

A draft form requesting data for populating a database representing how IG products are used is also included.

The requests below are in the form of a survey. The survey format was chosen over a database format to recognize the industry's opportunity to create a standard database format. The database should characterize sales numbers, design and manufacturer, service orientation and geography, and failure data which are all pieces of the durability puzzle and model validation. The project recommends selected pieces of this data be passed along to the industry in a sanitized form allowing companies to benchmark quality performance and increase industry knowledge. One location for the sanitization process and management of the data is IGMA, or a public but secure web site, such as the IG durability site. It is important to realize this is just baseline quality data for general use in and validation of the simulation tool.

Although the following request was originally submitted in support of the development of an insulating glass knowledge base, the project recommends a process developed by the industry and implemented to collect and utilize field failure data in a standard format. The gathering and use of data related to product performance is paramount for understanding the factors that contribute to insulating glass performance and durability.

The Data Requests

If you have received this survey it is because you are part of the value chain connected to the insulating glass industry. This could be through providing insulating glass (IG), components, manufacturing equipment, technology, insulating glass units or windows. This survey is intended to gather information on quality practices as they relate to product durability or service life in the IG industry.

At a high level, the first part of this survey is an attempt to understand what role the collection of field service data has in the assessment and improvement of product quality and durability. The second and more detailed part of the survey asks what specific data is being collected on actual product performance as it relates to service life.

Part I: Quality Management System

Part one of this survey centers on quality management practices that are in place in the insulating glass industry today. This data is a first step in providing a "state of the industry" report on quality management practices in the IG industry.

Each and every product has a set of requirements, explicit or implicit which define whether or not a product is acceptable. Ideally, these requirements are tied to the performance of the product in the hands of the customer. This is done by the development of some level of a product performance model, hopefully with respect to component and sub system requirements. Ideally these models are verified, through methods such as accelerated testing and comparative testing. Analytical product models developed to guild accelerated product development are finally validated when the product has fulfilled its intended purpose, which in many cases can be 20+ years in the field.

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The first part of this survey asks about what standards are, or may be, in place at your corporation that allow you to leverage field service data towards understanding what variables contribute to product performance.

Please answer the following questions as they relate to the product(s) that your company produces/sells.

1. What products used in the Insulating Glass Industry does your company produce (circle all that apply and identify quantities of different designs/formulations in the boxes)?

Desiccant	Sealant	Spacer	Glass	IG unit's	Windows	Adhesive	Other (please explain)

2. Does your company collect any data on the performance of your product in the field?

3. If you do not collect field performance measurements, are you aware of information from your customers that contains data on the performance of product or components you produce? (E.g. is performance data from an IG or window manufacturer made available to a desiccant manufacturer?)

4. What quality program does your company follow? This could be an internally developed program unique to your corporation, a recognized quality initiative (e.g. Six Sigma, TM-4000-02 Insulating Glass Manufacturing Quality Procedure Manual) or a 3rd party audited quality system (e.g. ISO 9001). Please explain the areas to which the quality program applies

5. What sources of information and systems do you have in place to collect field performance data (circle all that apply)?

Customer support data	(data obtained over the phone from a customer that has a product performance issue)
Warranty data	(time to failure and supporting data)
Field service data	(data on specifics of product features, location of install, etc)
Field return analysis	(analysis of failed product)

Regardless of whether you collect field performance data, how does your quality program validate product performance?

6. How is this data used in relation to other data you collect on your product? (Some examples might be manufacturing process data, accelerated test data, material specification data.)

Part II: Field Service Data Information Request

Part two of the survey is a request for information collected by IG or window manufacturers. However, data through other avenues that relate to IG performance are applicable.

Although it is the method that takes resources and effort, the best measure of insulating glass durability is the performance of product in the field. The collection and evaluation of this data can have significant impact on costs. This data can be collected actively (e.g. sampling of product in the field) or passively (e.g. waiting for a customer complaint). Although each has its distinct advantages, both are valuable measures of product performance. It is the intent of part two of this request to find out what data is collected on the performance of insulating glass units in the field.

In most cases field service data in the insulating glass industry will be collected by IG or Window manufacturers, this is especially the case for warranty data. If you are not a producer or seller of insulating glass units or windows but have information on the performance of your product in the field, your data is important and will add value to the results of this survey. Please answer the following questions to the best of your ability. This is not a request for the actual field data, it is an attempt to ascertain the state of the state of the industry.

SECTION 1: Window and Insulating Glass Unit Attributes

Please answer all that apply

Components

Insulating Glass units

1. Do you collect or have access to IG information as it pertains to your product?

   If so, what information do you collect or have access to?

   Dimensional (length, width, thickness)

   Glass thickness

2. What desiccant(s) do you produce or are used in the product(s) you sell?

3. What sealant(s) do you produce or are used in the product(s) you sell?

4. What spacer system(s) do you produce or are used in the product(s) you sell?

Box	U Channel	Corrugated Metal	Non-rigid	Barrier	Thermoplastic

5. What types of coatings or treatments are used in the glass you produce or product(s) you sell?

Low E Coatings	Clear/Clear	Tempered	Other	

Windows

6. Do you collect or have access to Window information as it pertains to your product?

7. If so, what information do you collect or have access to?

Unit color

Unit size (sash size if applicable)

Unit application (where, how, when installed)

Other

8. What style(s) of windows do you produce or contain in the product(s) you sell?

Double Hung	Casement	Glider	Picture	Roof	Awning

9. What <u>adhesives</u> do you produce or are used in the product(s) you sell?

10. What other components or finished products do you produce that are used in the manufacturing of insulating glass units?

SECTION 2: Failure Data

Please indicate which of the following information you collect about your product. This data pertains to the final product (window or IG unit). If you are not a producer of a final product but have access to the information as it pertains to the product you supply to the IG or window manufacturers, please answer the questions in this section.

1. Which of the following failure information is available for reliability\durability analysis?

    Manufactured Year
    Service Data
    Sales Data
    Size
    Type of IG application / Window style (e.g. Casement, Double Hung)

    Detailed window and glass information

    Service Data

    Sales Data

    Location of installed unit (region, state, city, zip)

    Service Data

Sales Data

Date of failure

Type of failure (e.g. internal condensation, weather strip)

Failed component (e.g. primary sealant)

Window condition at failure (e.g. wood deterioration, water in sash)

What other field performance data do you collect (e.g. direction unit is facing in home)?

5.0 Durability Testing

Michael Doll, Gerry Hendrickson

5.1 Introduction

Current metrics used in the IG industry to validate IG design, process and materials most commonly, if not entirely, center on physical testing. It has been known for some time that good IG design with bad materials or processes, or bad designs with good material, etc. create inferior IG units. From a consumer's point of view, one IG is pretty much the same as another and the failure of an IG is not generally associated with an IG manufacturer; the window manufacturer or builder gets the service call. The IG industry has proactively and cooperatively engaged in the certification of IG units in an attempt to assure that their customers (window manufacturers, builders, etc.) have a form of verification that the IG units will meet their expectations. Each IG producer (IG units are delivered as a component to window and door manufacturers and / or are assembled by window and door manufacturers in the window / door assembly factory) has the opportunity to achieve the level of performance necessary for certification and display the certification mark.

As discussed earlier, many IG producers use the designs, materials and process recommendations given from component suppliers. And, many IG production facilities have implemented suggested quality assurance processes across their IG production. Yet the certification testing was the activity that provided validation and assurance that the product would meet customer expectations, in the short and long term.

Several industrial organizations such as the Insulating Glass Manufacturers Alliance (IGMA), the American Architectural Manufacturers Association (AAMA) and the Glass

Association of North America (GANA), Insulating Glass Certification Council (IGCC) to name a few, offer processes and programs supporting quality IG manufacturing and certification. There are many testing laboratories that provide the specific certification testing services which are based on and supported by ASTM standards, protocols and procedures. The following discussion explores the methodology of accelerated durability testing, the current tests, the perturbation of failure modes (magnitudes, durations, frequencies, etc.). It also suggests comparison to environmental data and field/laboratory measurements, as tests are considered for the durability simulation validation and advancement of IG testing methodology, protocol, and procedure with a focus on IG durability.

5.2 Development of Accelerated Tests Correlated to Service Life

Development of accelerated tests that have comparable results to actual field experience is not a trivial matter. To properly evaluate the IG requires that each of the materials and their interfaces to adjacent materials be examined in a manner that allows each type of failure to be clearly identified. Only by this rigorous methodology does a clear picture emerge that enables assessment of the particular material and process details. The FMEA work done in this project begins a comprehensive list of potential failure points and areas of concern. The existing test protocols by ASTM, SIGMA, and the European standards group is a start at evaluating IG life. As expressed in the section on environmental exposure, these existing tests are not as severe as actual exposure conditions in all parts of the country. These existing tests also are a composite of multiple stresses and do not give a clear picture of the exact cause of a failure.

5.2.1 Definition of Accelerated Testing

Accelerated testing is testing designed and implemented in a manner that allows the determination of product service life in a shorter period of time than actual field exposure and use. Actual field service life prediction determined from units installed in the field is the true life; given the exposure conditions they actually experience. There is an expectation that the "average" unit sees a milder exposure than the most severe exposure. At this time there is no generally accepted correlation of minimum, average, and extreme exposure. There also is an expectation that singular or seldom experienced field conditions cause stress that initiates more failures than the average stress condition. For example, the sudden brief drop in barometric pressure from a thunderstorm or hurricane may shorten the service life of an IG unit far more then a longer time of moderate barometric pressure. This is another way of stating that the reduction in service life is not linear with the differential in stress from average.

While actual field experience is the ultimate basis of product reliability, there is a need for more immediate knowledge of product performance to avoid future product failures. Test methods for accelerating results must be soundly based on a high degree of correlation with actual field experience. To achieve this correlation, detailed data of a large number of units correlated with their field life will give the assurance that the test methods are appropriate.

Accelerated Testing Methodology

Acceleration of product service life exposure can be achieved by testing units at increased stress levels, increased number of cycles, and increased strain levels. The relationship of changes to these factors to actual service life needs to be determined to a higher level than at present. Producing test units with variation in design and process to vary the strength level will help in gathering this data. Comparison testing of these test units in any proposed test procedures as well as in field exposure is needed.

Comparison results for proposed and actual IG designs can be produced by acceleration factors such as increasing the number of cycles run and modifying the strength of some sample components.

5.3 IG Durability and Current Accelerated Testing

Appendix 5 presents an expanding list of current IG related tests representing US, European and Canadian Standards. The list represents published, commonly distributed test procedures, many of which have already been referenced in this report. In addition to the protocols and procedures presented, many private companies in the IG value chain have developed tests which provide a specific set of validating data relative to their chosen business model.

The tests listed in the appendices are discussed here and recommendations made in consideration of:

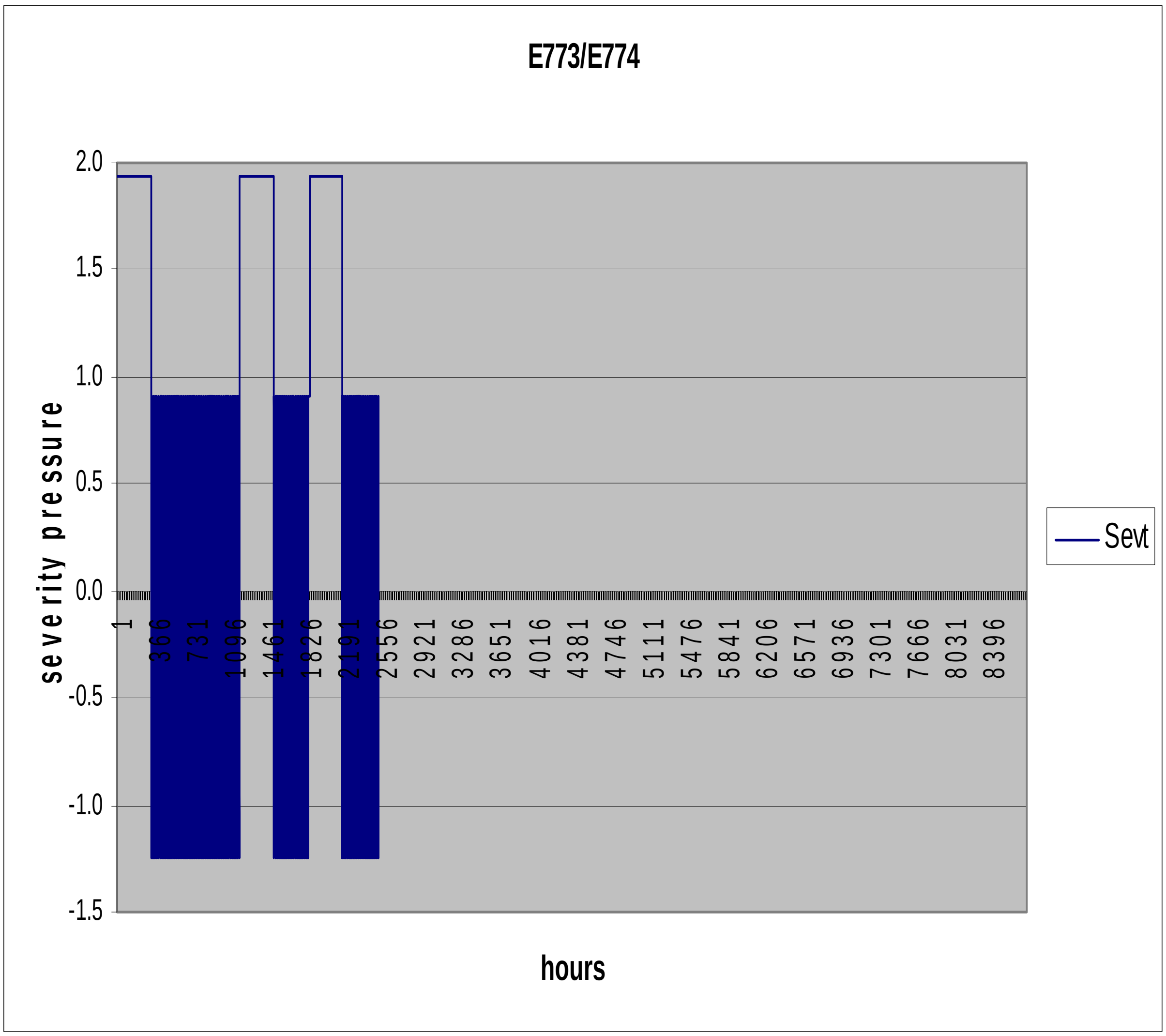
- Comparing the overall severity factor to the calculated environmental severity factor in psi- hrs
- The resolution and type of test data and the opportunity to identify root cause failure
- The ability of the test to induce stress to one or more identified failure modes

5.3.1 Current Testing and Expected Environmental Stress

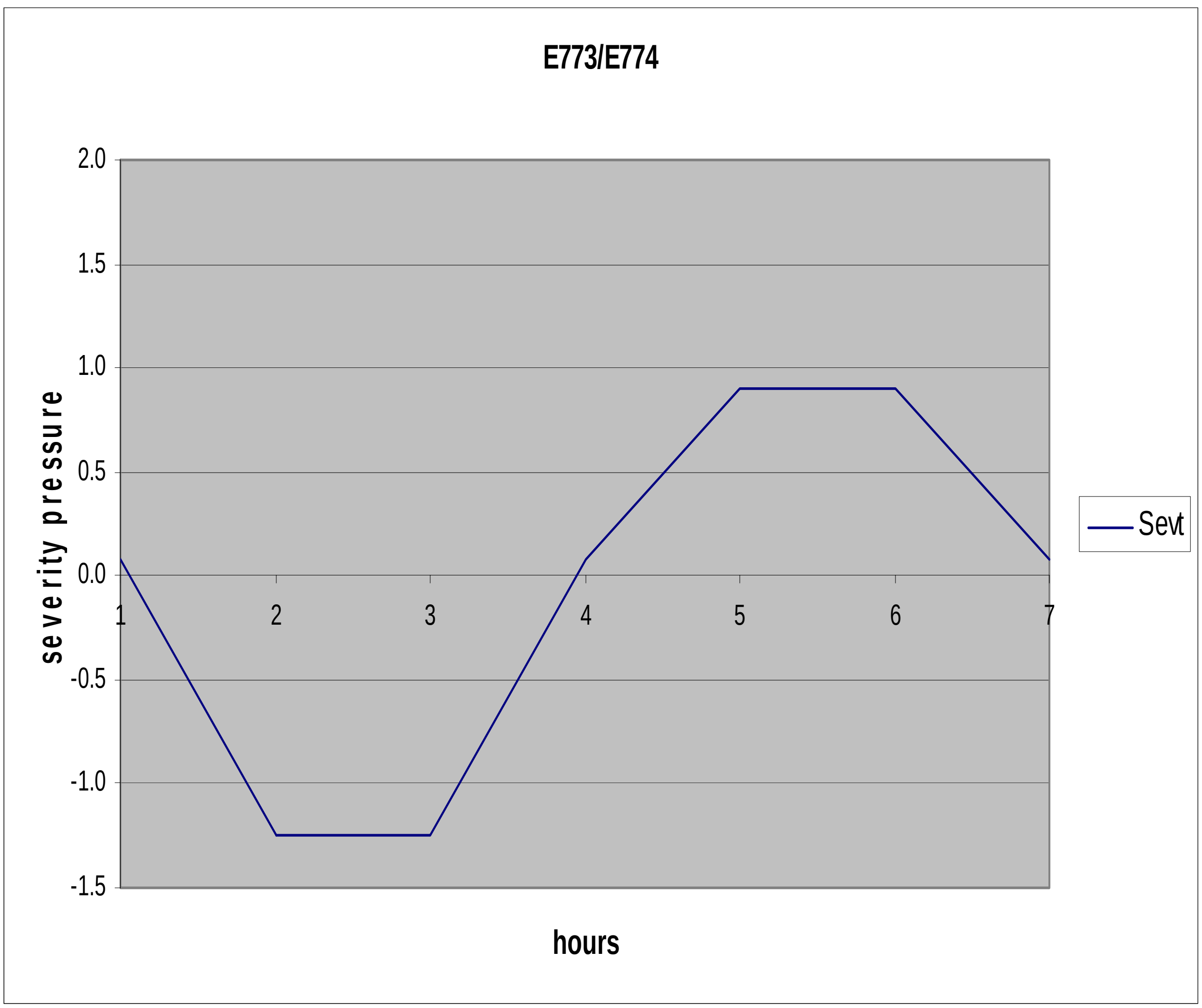
As can be seen from the severity values computed from actual weather data and from the severity values found in the current ASTM and EN test standards, there is a considerable gap which can be filled in with revised tests to give realistic durability test results. Development of dependable IG unit service life predictions will be well served by test methods which exercise the IG through the full range of expected stresses in actual building installations. Sufficient units exposed to testing also will enable statistically valid computation of service life expectancy. Test loads and severity related to each aspect of IG materials and construction will enable improvements in manufacturing methods and materials to produce units with reduced failures. Development of these new tests is not overly difficult. Validation of the test methods with actual field experiences is more difficult. What is needed to verify the tests is corresponding field testing of units with well documented construction similar to the units placed in accelerated testing. The failure analysis of both the field tested units as well as the accelerated test units will give the specific data for analyzing the cause of failure and improve IG design.

ASTM E 773, E 774, E 2188 and EN-1279-2, EN-1279-3 were analyzed for severity as a comparison to actual weather files. File “Durability_comparison.xls” contains the calculations. The comparisons are presented below.

Graph of ASTM E 773/E 774 test plotted on scale of 1 year total time (8760 hours). Severity pressure in psi for high humidity and cycling portions of the test with the first cycling portion ending in a C rating, the second cycling portion ending in CB rating, and the final cycling portion ending in CBA rating.

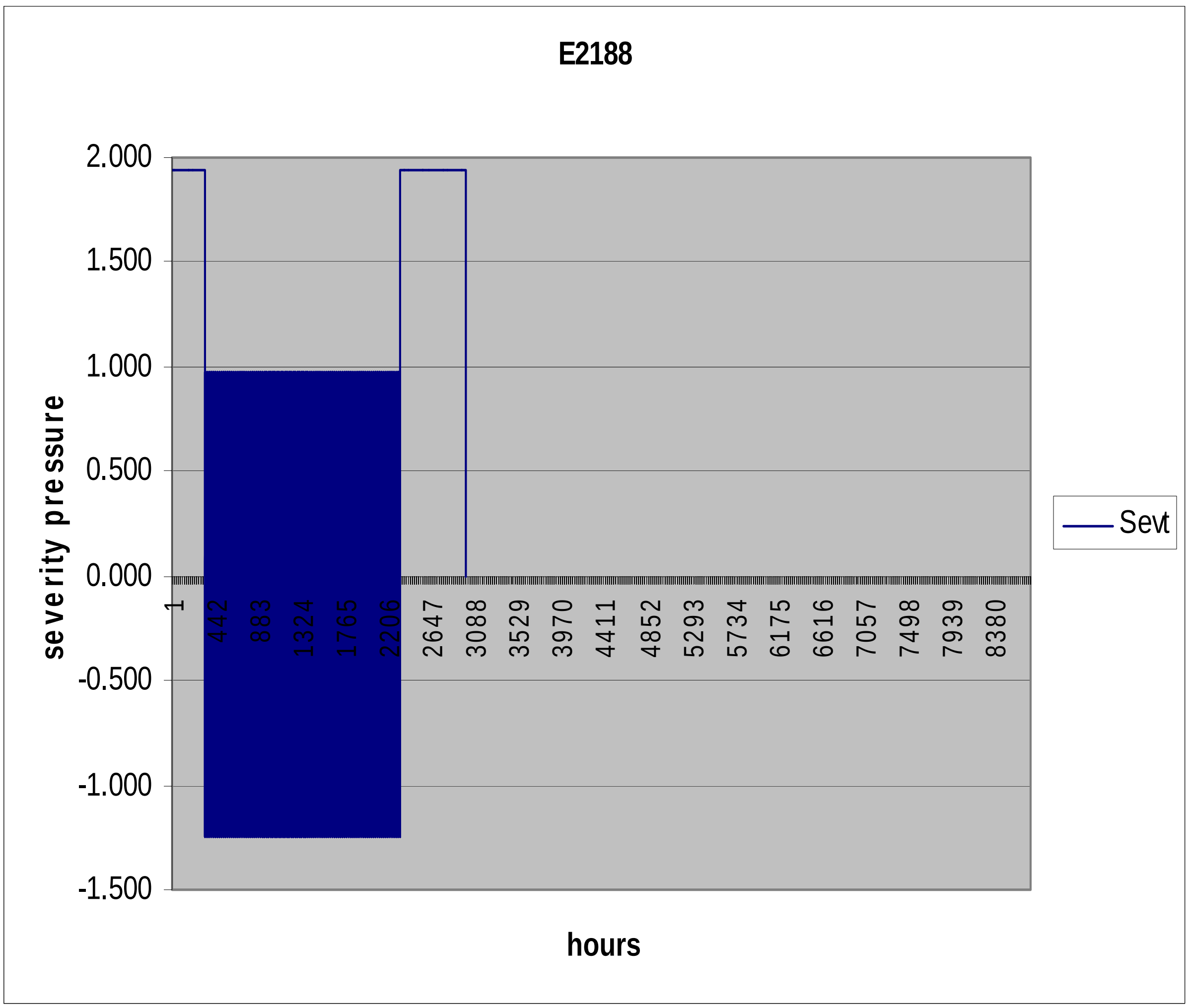


This graph shows one cycle of the cycling portion of E773 in terms of psi severity pressure. The cycling portion of this standard has one surface of the test sample exposed to a varying temperature and the other surface is exposed to room air. The high humidity portion of the test has the entire sample in an immersion type chamber where the internal IG temperature is the temperature in the humidity chamber.

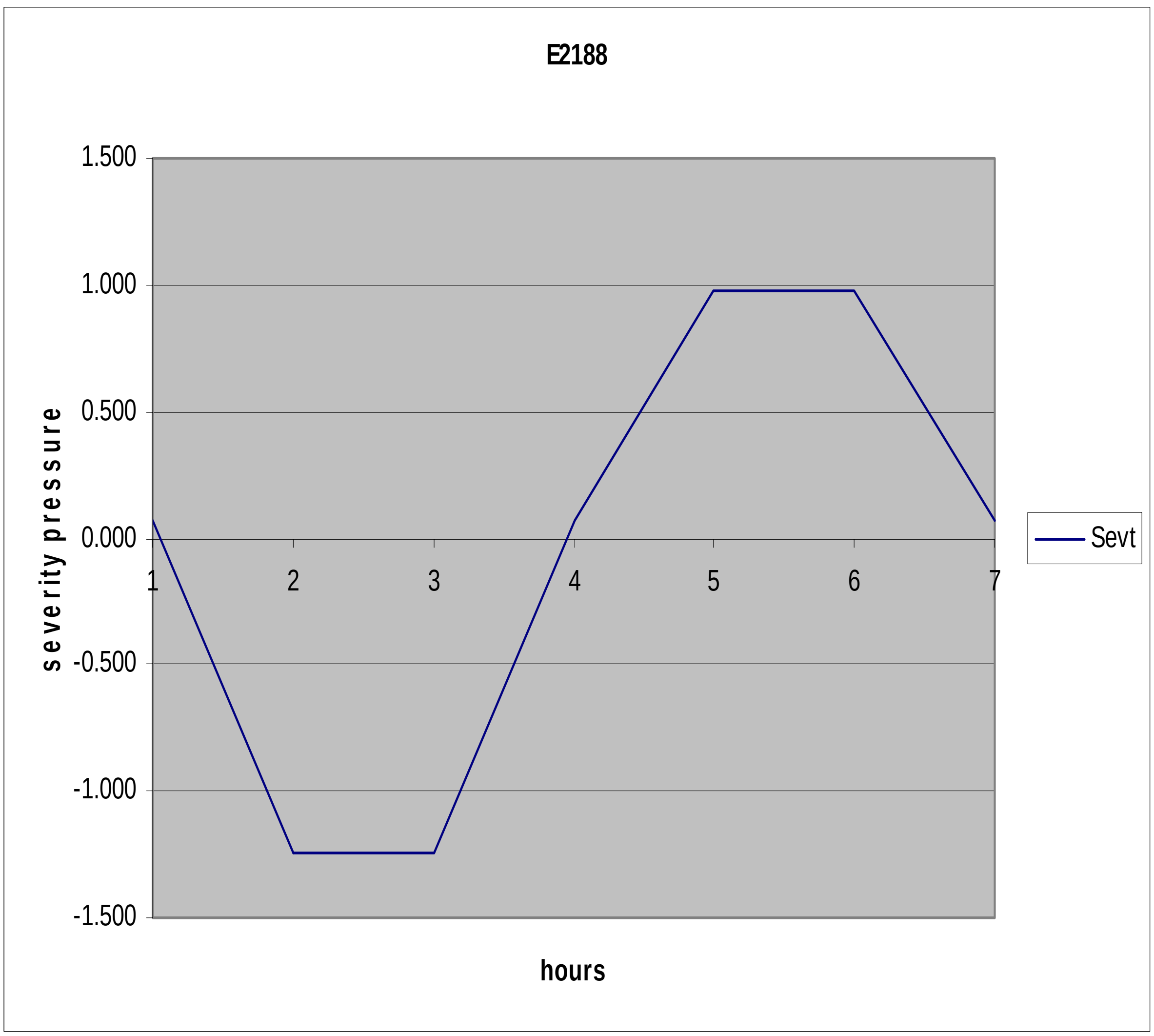


Graph of ASTM E 2188 test plotted on scale of 1 year total time (8760 hours).

Severity pressure in psi for high humidity and cycling portions of the test with the first high humidity portion preceeding the cycling portion and the final high humidity portion following the cycling test.

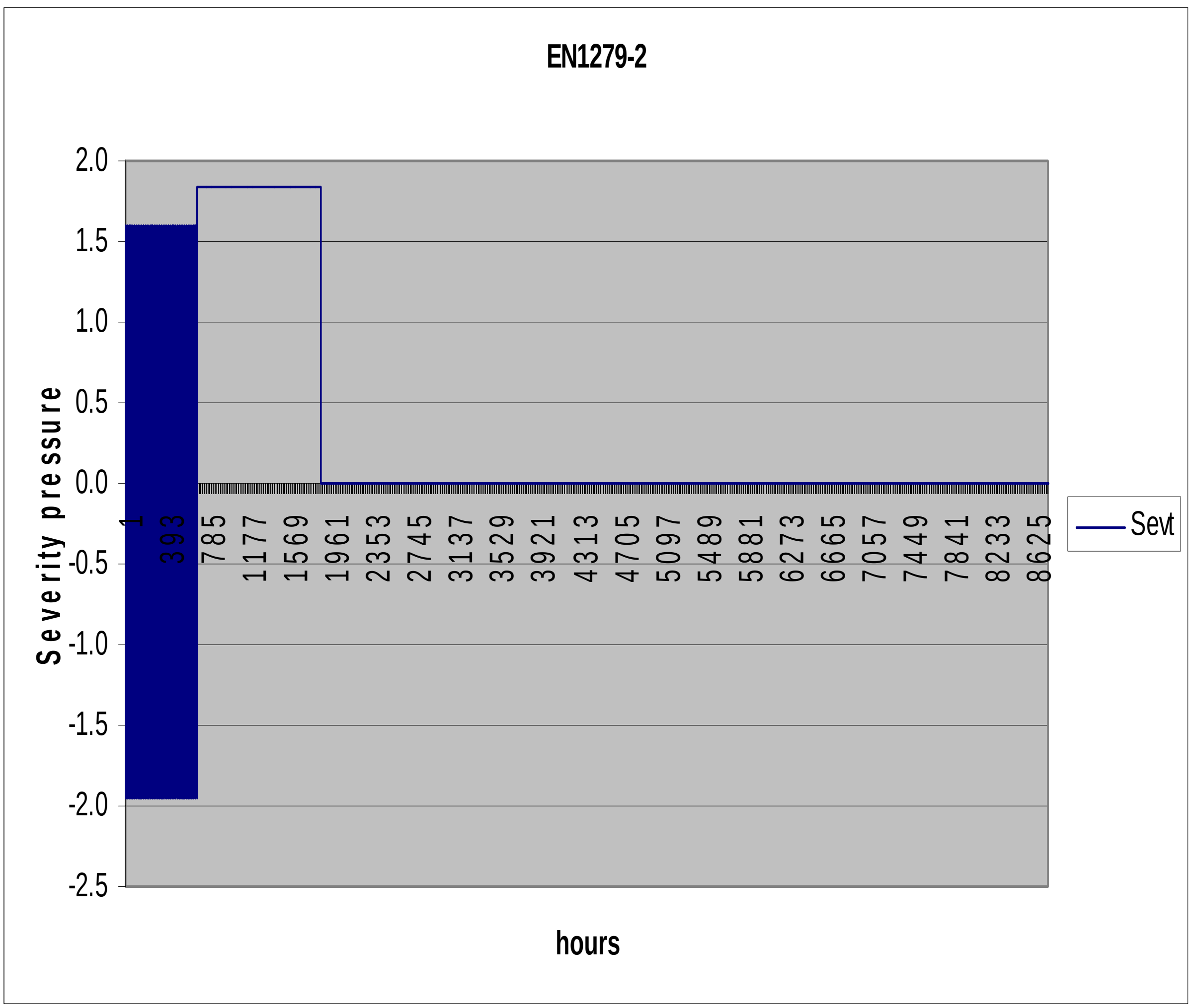


This graph shows one cycle of the cycling portion of E 2188 in terms of psi severity pressure. The cycling portion of this standard has one surface of the test sample exposed to a varying temperature and the other surface is exposed to room air. The high humidity portion of the test has the entire sample in an immersion type chamber where the internal IG temperature is the temperature in the humidity chamber.

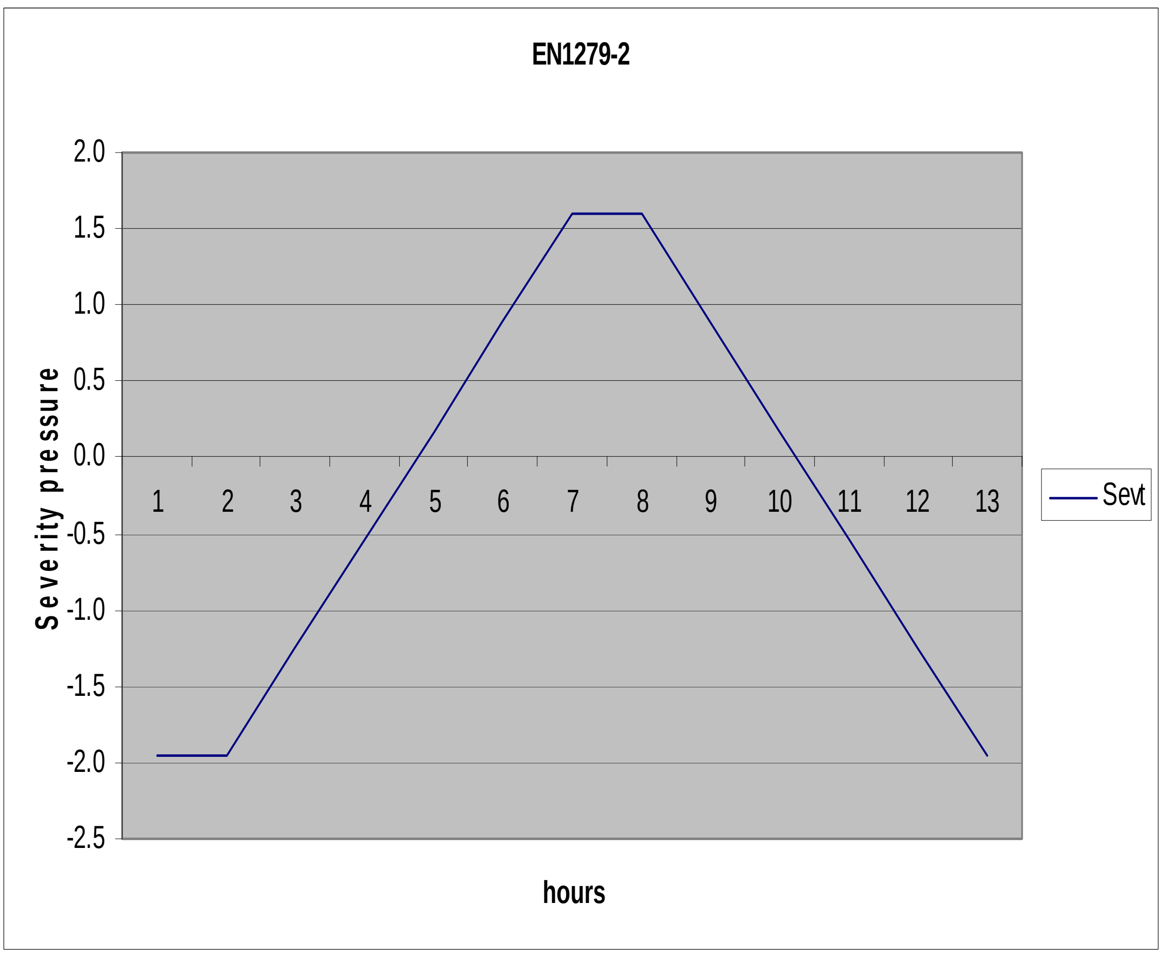


Graph of EN 1279-2 test plotted on scale of 1 year total time (8760 hours).

Severity pressure in psi for high humidity and cycling portions of the test with the high humidity portion following the cycling test.



This graph shows one cycle of the cycling portion of EN1279-2 in terms of psi severity pressure. The cycling portion of this standard has the entire IG immersed in a temperatuer chamber where the internal IG temperature is the same as the chamber temperature. This method results in a higher severiuty pressure than the ASTM test methods. The high humidity portion of the test has the entire sample in an immersion type chamber where the internal IG temperature is the temperature in the humidity chamber.



The ASTM tests have temperature-pressure severity ratings of 0.906 to -1.244 psi for E773/E774 and 0.975 to -1.244 psi for E2188.

The EN1279 tests have 0.800 to -0.972 psi.

Hours of exposure to the severity temperature ranges expressed in degree F-hours from 78275 for E773 CBA rating, 80795 for E2188, 25361 for EN1279-2, and 12681 for EN1270-1279-3.

Vapor pressure cumulative severity is 2767 psi-hrs for E773/E774 and E2188, 3095 for EN1279-2, and 1768 for EN1279-3.

Test Comparison Summary	ASTM E773 E774				ASTM E2188		EN 1279-2		EN 1279-3	
	C	CB	CBA		durability		durability		gas loss	
Weather test	F	F	F	C	F	C	F	C	F	C
Temperature (max)	135	135	135	57	140	60	127.4	53	127.4	53
Temperature (min)	-20	-20	-20	-29	-20	-29	-0.4	-18	-0.4	-18
Cycling (days)										
No. of cycles (N)	140	196	252		252		56		28	
cycle length (hrs)	6	6	6		6		12		12	
total cycling (days)	35	49	63		63		28		14	
Severity – temperature pressure										
maximum (psi)	0.906	0.906	0.906		0.975		0.800		0.800	
minimum (psi)	-1.244	-1.244	-1.244		-1.244		-0.972		-0.972	
Severity – temperature pressure in units of psi-hours (entire cycling test)										
above 0 psi (psi-hrs)	264.6	370.4	476.28		511.2 2		113.6		56.8	
below 0 psi (psi-hrs)	338.6	474.1	609.5		609.5		135.4		67.72	
Time at temperature per cycle in (degree F-hours)										
above 70 F	135.4	135.4	135.4		145.4		181.4		181.4	
below 70 F	175.3	175.3	175.3		175.3		271.5		271.5	
Time at temperature entire cycling test in (degree F-hours)										
above 70 F	18949	26529	34108		36628		10159		5080	
below 70 F	24537	34352	44167		44167		15202		7601	
High humidity	F	F	F	C	F	C	F	C	F	C
Temperature	140	140	140	60	140	60	136.4	58	136.4	58
% RH	95	95	95		95		100		100	
duration (days)	14	28	42		42	14 +28	49		28	
severity (psi-hrs)	922.3	1845	2767		2767		3095		1769	
no. of units	6	6	6		6		6		6	
end dew pt	-30 F	-20 F	-20 F		-40 F					
moisture penetration index	x	x	x		x		20%		x	
gas leakage	x	x	x		x		x		1	%/ yr

The existing ASTM and EN test standards serve as a basic screening procedure which helps catch some production errors. The sample sizes are too small for meaningful statistical life predictions. The test duration and severity are very mild compared with a ten or twenty year expected service life. The combination of loading conditions makes cause of failure data difficult to produce. The ASTM test standards allow new sets of units to be tested in the event of a test failure. As long as a set of units passes the test, the manufacturer is certified for a period of time. The EN tests also include materials testing to assist in the consistency of production and materials. Both the ASTM and EN standards call for testing of specific unit sizes and construction. There is no quantifiable data on the relationship of these test units with the full range of sizes and shapes actually produced. New test methods and procedures will help to develop this correlation.

If no new test methods are developed and implemented, no further progress in IG unit durability is foreseen except that undertaken by a few IG component manufacturers in support of their own products. Captive testing by manufacturers leads to proprietary data which is not readily shared by the industry. An example of past testing is the SIGMA field test where units built by various companies were placed on test in various parts of the country. The exact unit construction details were disguised to protect the manufacturers and failure data can not be related to construction details for meaningful analysis.

5.3.2 Identified Testing Opportunities

To clearly show the true durability aspects of each segment of an IG detailed construction, tests that exercise that segment are needed. Only by knowing the exact failure and the stresses that caused the failure can advances be made in the materials used and in the processes used in building an IG.

A list of these segments follows:

Adhesion of sealants to the glass

Adhesion of sealants to the spacer

Water absorption of the desiccant

Glass cleanliness

Thermal expansion of the glass and other materials

Torsion loading on the IG unit and sealant system

Gravity loading of one lite of glass

UV exposure of the sealants

Humidity exposure of the sealants

Impact loading of a unit by the operator

Pressure cycling of the complete IG unit

Wind loading test of the IG unit

Thermal cycling

Desiccant desorption with thermal cycling

Suggested Tests for Development

1. Pressure Characterization Test (validation of strength)

This test would place IG units in a pressure test vessel and cycle the units from room ambient conditions to plus and minus 2.5 psi, at a 70 F constant temperature. Center of glass thickness would be measured. When the center of glass thickness equals the edge thickness, the equivalent manufacturing conditions would be met under controlled conditions. This would quantify the varying barometric pressure and plant temperatures at which the IG unit was sealed. Center of glass thickness at some specified conditions above and below the sealing value would give data on the rigidity of the sealant and spacer assembly.

2. Pressure Cycling Test

IG units would be placed in a pressure chamber and pressure cycled. The pressure limits may be based on the geographical location of typical installations as determined by the severity calculations previously described. Number of cycles would be representative of the desired service life of the unit. Temperature conditions could be varied from low to high, keeping in mind the total severity condition being applied to the unit.

3. Temperature Differential Test

For this test, IG units would be placed in a fixture that allows a hot and cold water spray to be applied to each side of the assembly. After a period of time to stabilize, the hot and cold sprays would be reversed. This test is to stress the glass and adjacent seal in shear due to the thermal coefficient of expansion of the glass. The number of cycles should be appropriate for the installation location, as would be the temperature settings. Acceleration of the test results would be from a high number of short term cycles (each cycle would be approximately 3X the thermal time constant of the IG unit). For a 9.75 inch sample length, the change in length for a temperature range of 0 F to 140 F is: 0.0107 inch for glass; 0.0277 inch for aluminum; 0.0198 inch for stainless steel; and 0.0136 inch for steel. These values place a substantial shear stress and elongation on the sealants.

4. Twist (Torsion) Cycling Test

This test would subject IG units to a twisting force similar to that seen in casement style windows during operation. A torsional force may also be applied to some units from their installation in a building when the window unit is forced into alignment with a wall surface. The torsional stress causes a high shear stress in the sealant. A measurement on the torsional stiffness of an IG will give data on the sealant system rigidity. The test parameters would be based on the shear stress allowed in the sealant material specification. Test rate and number of cycles, temperature, etc. needs to be determined.

5. Static Shear and Creep Test

In this test one lite of the IG unit would be supported and the other lite unsupported. A load would be applied to the unsupported lite sufficient to place the sealant materials near the shear stress allowed in the sealant material specification. Measurement of the amount of movement of the unsupported lite gives the creep of the sealant after a period of time. The temperature at which the test is run needs to be determined.

6. Temperature Cycling Test

In this test the entire IG would be placed in an immersion type chamber and the temperature cycled. Number of cycles and temperature extremes needs to be determined.

7. Sealant UV Exposure

Sealant applied to test strips of glass 1 x 3 inches would be exposed to UV light and moisture for a period of time. The force needed to pull the glass test strips from the sealant would be measured. The modulus of the sealant also would be checked for changes during the test.

8. Interior IG Dew Point

An improved method of measuring the interior dew point is needed. The existing method uses a fixed temperature cup and takes a significant amount of time to equalize and determine whether moisture is present on the inside of the glass. If the reading needs to be repeated for another temperature, the total test time is very long. A new method of using a test probe with a decreasing temperature ramp would speed up accurate dew point readings. Another method worth further development would be a dew point sensor sealed inside the IG unit. An internal battery powered readout placed inside the test units would give a continuous reading of actual dew point. For more power a solar cell powered device may work with light applied briefly when a reading is required.

9. Material Tests

Tests of the IG components and materials are required to give data on the characteristics of importance to longevity of the IG.

a. Glass cleanliness

b. Edge deletion quality

c. Spacer leak rate. (Roll formed spacers may contain microscopic fractures at sharp longitudinal bends.)

d. Sealant viscosity, modulus, adhesion, elongation, shear strength, tensile strength, composition, permeation rate under stress, and other characteristics

e. Desiccant absorption, desorption, capacity,

f. Spacer surface finish, contamination, and sealant adhesion test.

g. Other tests.

10. High Humidity Soak Test

The present ASTM standards call for a humidity soak test at 140 F for a total of 42 days. EN-1279-2 calls for high humidity testing at 136.4 degrees F (58 degrees C) for 49 days. This corresponds to 2767 and 3095 vapor pressure psi-hrs duration respectively. Weather data for the US for 1990 to 1995 gives average annual vapor pressure psi-hrs values from 362 to 3357. Ten (10) years of actual exposure would then have the equivalent range of

3620 – 33570 psi-hrs. To produce a high temperature/high humidity exposure equivalent to 10 years actual service life would require either a longer test exposure time or a further accelerated test procedure. To accelerate this procedure, just raising the temperature would produce an unrealistically high stress on the sealant system. Placing units in a heated pressure chamber would enable a more severe high humidity test without otherwise affecting the test unit. The vapor pressure is raised to counter-act the deflection of the glass caused by the test temperature. When the temperature is raised to 180 degrees F @ 95% RH, the vapor pressure raises to 7.298 psi. With an increase in pressure of 1.525 psi, the deflection of the glass will be near zero and the sealant unstressed mechanically. This will develop 184.4 vapor pressure psi- hrs per day of test exposure. For a 10 year equivalent, 182 days exposure will be required for the most severe actual exposures. A realistic 10 year test of a moderate climate humidity exposure such as Minneapolis could be run in as little as 61 days.

11. Impact Test

One lite of an IG would be mounted vertically in a rigid frame which moves in a vertical direction. The other lite would be unsupported. The frame would be raised and allowed to drop vertically onto a heavy base. The resulting shock would be similar to that experienced by a double hung window sash which drops or is slammed closed. Number of cycles and temperature will be determined.

In development of these and other new test procedures, it will be imperative that each and every test be quantified with actual field experience. During this development process, new and additional test procedures will become evident. Refinement of test details will enable the new tests to more closely correlate with field exposure. An important aspect of this testing will be the failures produced. Failures during testing enable accurate identification of failure causes and the knowledge to improve the quality of IG units. Failures are also required to produce statistically valid results.

Further testing and evaluation methods have been documented in the IG industry or by test agencies and are not further described here. The field of reliability engineering has a great deal to offer in this endeavor.

All of the above tests and evaluations need to produce results capable of being evaluated by statistical methods appropriate to the expected service life of the IG units under test, for example, an expected service life of 20 years with 20 % total accumulative failures. Sufficient sample quantities and test duration are required to produce meaningful results. The existing ASTM and EN standards are a start in this direction, but do not presently have the capability required for success. Ref: ASTM standard: E 632-82(1996) Standard Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials. This standard contains information of value in determining whether a proposed new test may help in proper prediction of service life. Other aspects of accelerated testing are well known in the testing of commercial and industrial products.

It is important that any proposed IG tests be evaluated in terms of the stresses and strains that IG units see in actual building applications. The final suite of IG tests needs to address all of the stresses and conditions to which an IG is exposed. Advancement in materials and workmanship will require close attention to all of the details.

Total IG durability or reliability is the product of all of the separate test reliability Figures:

$$R\,(ig) = R(t1) \times R(t2) \times R(t3) \times R(t4) \times R(t5) \times R(t6) \ldots\ldots$$

Each separate test reliability (Rt1, Rt2 ...) would be calculated by the appropriate method based on whether the test results are random or wear-out failures. It is imperative that each test is given the proper weight and life expectancy conditions so the overall reliability (durability) calculation is based on the same total over-all service life expectancy. Once the reliability is known for a period of service life expectancy (for example 1 year) then the reliability at any other service life can be calculated with:

R(x yrs) = R (1 yr) ^ x.

One caution with this calculation is end-of-service life wear-out failure. If the test is not run for a time sufficient to detect end of service life failures, the calculated reliability will be higher than the actual reliability.

The following chart shows the relationship of reliability with service life when the failure rate is constant. A 1 year reliability of 0.98 is equivalent to a five year reliability of 0.90 and a ten year reliability of 0.82. The reliability value is the expected number of units to survive the period of time that the reliability is based on. (A reliability of 0.82 would mean that 18% of the initial units have failed.) If a 20 year reliability of 10 percent total accumulated failures is desired, the equivalent 1 year reliability is 0.995. Using the chart will give an appreciation of the 1 year reliabilities required to achieve durable IG units for a given total service life time. The statistical basis for calculation of random failure reliability and wear-out failure reliability is available and will not be further discussed here. From the expected reliability values required for adequate IG unit life, the number of units tested can be calculated assuming no failures. Random failure testing must be run to the minimum number of cycles required for the desired service life. Wear-out failure testing must be run until at least two units have failed to properly calculate the reliability. When four factors of service life are present and each factor is tested independently, the total reliability is the product of the reliability calculated from each test. If all four factors are equivalent, to achieve a total reliability of 0.90 requires that each factor have a reliability of 0.9745 or greater. As can be seen from the durability tool portion of this project, the number of factors far exceeds four.

Life years	1	2	5	10	20
Reliability	0.80000	0.64000	0.32768	0.10737	0.01153
Reliability	0.90000	0.81000	0.59049	0.34868	0.12158
Reliability	0.95000	0.90250	0.77378	0.59874	0.35849
Reliability	0.97500	0.95063	0.88110	0.77633	0.60269
Reliability	0.98000	0.96040	0.90392	0.81707	0.66761
Reliability	0.98890	0.97793	0.94574	0.89443	0.80000
Reliability	0.99191	0.98388	0.96018	0.92195	0.85000
Reliability	0.99475	0.98952	0.97400	0.94868	0.90000
Reliability	0.99744	0.99488	0.98726	0.97468	0.95000
Reliability	0.99873	0.99747	0.99369	0.98742	0.97500
Reliability	0.97793	0.95635	0.89443	0.80000	0.64000
Reliability	0.98388	0.96802	0.92195	0.85000	0.72250
Reliability	0.98952	0.97915	0.94868	0.90000	0.81000
Reliability	0.99488	0.98979	0.97468	0.95000	0.90250
Reliability	0.99747	0.99495	0.98742	0.97500	0.95063

5.3.3 The Role of Documented Product and Testing

An essential element in producing products with firm expectations of durability is the engineering documentation of the product. Without the documentation, changes in materials and process can creep into the production line and produce deviant units whose tendency to fail early may not be noticed until years of field exposure have occurred.

Documentation starts with engineering specifications which clearly show the design goals, the durability expectation, the nature of the design, and the exact details of each part and aspect of producing the IG units. The specifications must include all aspects of the manufacturing process to avoid inadvertent changes. Part drawings must show dimensions and tolerances that are of significance.

Another part of the documentation is the set of material specifications for each of the materials that are incorporated in the IG as well as detailed information of all materials that may come in contact with the IG during its assembly. The quality of an IG may be significantly decreased by such auxiliary items as the type of hand cream used by production employees. Building units for the rigorous durability desired requires much more attention to detail than nearly any other part of the building construction process.

Verification of durability by testing depends on building the test samples in exactly the same way and with the same materials and process as will be used in production. The verification is not so much testing the sample IG units as it is testing the specifications and process capability to produce durable units.

6.0 Results and Discussion

Michael Doll

The United States Department of Energy and the IG industry continue to coordinate an interest in understanding and addressing IG durability opportunities. Business objectives in a competitive market make the task of coordination and dissemination of related IG durability information tenuous at best and must be addressed with all consideration. The support for creating a knowledge base to evaluate the current understandings was envisioned to provide an opportunity to consolidate provided information and data to document what is known and what is unknown about IG durability. In addition, a methodology was presented to document and direct continuing research to identify and address the root causes of IG failure. As can be expected, discoveries will suggest short and longer term improvements in IG design, materials, process and the quality implementation of each.

Although there may be continuing debate around the actual number of IG failures, current data collected by industrial organizations and private companies support the original assumption that about 10% of IG fail at a level recognizable to the user within the first 10 years of application. In fact, this may be a conservative failure rate with infant failures possibly making up the majority of the assumed 10%. Energy loss implications and degrading consumer confidence continue to facilitate concern in understanding and addressing the issues. Meeting future energy requirements will require that new, initially costly, technologies be integrated in IG products and these advancements must be supported by consumers and businesses achieving expected durability goals with confidence. Long term development and improvements will only be implemented and expanded, reducing cost and expanding availability and use if an unquestionable advantage is demonstrated.

The current expectation for the service life expectancy of a window many times is communicated in terms of the service life of the building in which the unit is installed. Generally, windows are considered a part of the wall and thus command the same expectation for dependable and efficient use over time. Although building service life expectations are commonly viewed in terms of generations, the durability expectations of the components generally are defined by related warranty periods. In the window industry, acceptable product warranties are delivered spanning 20 years, and some much less. At the present time, it seems as though describing IG durability in terms of a twenty year service life is an acceptable description of expected IG durability.

Assuring 20 year IG durability is not a trivial matter in consideration of the expected stresses (magnitude, frequency and variability) imparted on an IG system over a 20 year service life and the response of the IG system to those stresses. As has been demonstrated, the environment induces a complicated, ever changing set of stressors on the system. These stresses involve a range of stressors from the chemical UV and water considerations to the obvious barometric pressure and wind changes. For the most part, it is difficult to predict these stress magnitudes and frequencies of application acting on the system and how they may be interacting with each other. Historical weather data provides an excellent statistical foundation for developing reasonable expectations for IG performance. The development and presentation of severity factors as a way of viewing many meteorologically varying geographical locations from the same perspective simplifies the opportunity to compare expected IG applications. Continuing severity factor development can integrate additional environmental stressors such as UV and wind load.

As the ever changing set of stresses acts upon the IG, the IG system is continually responding. The system seems to be simple in design, with most IG designs containing only four to five material components. Yet, the material and system response is as complicated as the stresses acting upon it. Easily envisioned wind force or pressure changes act against the designed material properties. Not so easily envisioned forces such as UV act against the molecular bonds of the material. The commonly chosen sets of IG materials are inherently sensitive to many of the environmental inputs. A portion of the IG durability response must consider the changing material properties over time. Each of the materials has been chosen to provide strength to the system and each material has some dependency on adjacent materials to provide that expected strength over time. Thus, the interaction at the material interfaces, the interaction of changing material properties and the overall stress inputs all combine to create a possible system of failure modes which must be identified and their relationships defined. The Failure Mode and Effects Analysis (FMEA) tool has been presented as an innovative approach to identifying and documenting recognizable IG system failures and the paths (or maps) that lead from root cause failures to the system failures.

As has been discussed, improved IG durability must be addressed through each of the design, material and process activities. Understanding expected product usage, the environment in which the product is intended to survive, the material choices available to meet those design requirements, along with addition information, are necessary for a successful design. From the designer's point of view, capturing and resolving the varying environmental data, the varying stresses imparted on the system, the material and system response and the entanglement of interactions is required to engineer a durable IG system. In consideration of the obvious amount of data to consider, one way to approach the design activity is to develop a set of simplifying assumptions which are hoped to provide a conservative solution to the durability challenge. Presented here is the suggested solution, the development of a computer based IG durability design modeling tool. Using the power of existing computer technology, the data can be addressed, analyzed and produce results which support definition and direction for improved IG durability.

Challenges with creating a computer based durability model are no less intimidating than trying to apply the data to a single design. The process required an initial set of simplifying assumptions and compromises to give focus to the basic material modeling. The results of the materials modeling include a series of differential equations, solved simultaneously and coupled through their common variables. This time-step based approach provided for a system simulation as if in real time but lacks the direct ability through probabilistic calculation to follow complete systems failure to probable root cause in an efficient manner. In consideration of this initial development, the durability model provides a valuable foundation for final development of the Fault Tree Diagrams as presented in the referenced Phase I report.

This is the first simulation of its kind developed for the fenestration industry with possible extension to many areas of the building envelope. The tool remains very flexible as continued development is anticipated in the areas discussed in this report. In addition to implementing a simulation tool to handle the required input data, calculation and output, this tool provides the opportunity to simulate the expected service life cycle in hours relative to days or years. This is an important and needed development in the ever accelerating material and product development environment.

The initial stages of program debugging, sensitivity analysis and advancement has begun and substantial work remains to be completed to meet the original goals. Yet, the current model holds the capability of assisting in prioritization and direction of IG durability research and advancement. In addition, a designed iterative process can utilize the simulation to advance current and new durability testing protocols and procedures while advancing the simulation response. This process will include designing the simulation input to model the laboratory test environments and building a direct correlation to measured and observed laboratory IG failures.

Input into the simulation tool is based on the IG design and application; whether the application is defined as a laboratory installation or customer installation. In its current version or future advancements, the simulation requires input that is representative of a comprehensive understanding of the IG design, materials, processing and its anticipated application. This requires a comprehensive product and engineering specification be developed. In fact, the required understanding of the IG system must have the depth to include clear expectations of the material behaviors throughout their expected service life.

The need for a product and engineering specification activity can not be stressed enough in this, or any, development and manufacturing process. These specifications or product requirements establish the baseline for the comparative analysis and development processes. As more is learned, the requirements are updated and the documents revised. For example, with a comprehensive set of inputs, IG durability of a specific design can be compared in different locations of usage as demonstrated in this report. Or, a material or property can be compared to each other and their expected or improved durability. Another example would be comparing a material property at one end of its processing variance to the other end on its variance.

The durability tool as developed by Aspen Research Corporation and TNO, in its present form, is limited to the theoretical concepts, as previously discussed. There is a need to validate the tool with actual field installed IG units in a variety of geographical locations and building construction types. Attempts were made during this Phase of the project to obtain field failure and failure cause data from manufacturers with very limited success. No hard published data is available in the IG industry. The IGMA long term study has not released manufacturer's identities and specific IG constructions details with the results data for proprietary reasons.

The previous sections have shown that actual IG environmental stresses vary with location and installations. Testing standards now used are limited in how well the tests stress IG units for determining durability values. Development of additional IG testing methods and tests to allow realistic determination of failure modes and causes and calculation of reliability values will allow the details of materials, process, and design to be specified in sufficient detail to allow the accurate prediction of IG life.

Currently the IG industry tests IG units to IGMA and ASTM standards as well as European standards as required for validation and certification. This level of testing and certification has had many benefits to the industry in terms of preventing massive IG failure rates in the first several years of exposure. As has been documented, certified units displaying the certification markings have been involved in large and small scale IG failures found on certain building projects. The most notable has been the common problem with excessive deflection found in Argon filled IG units from many manufacturers in many areas of the country. The overall success rate of IG manufacturing is good. However, the cost of replacing failed units in terms of actual expense and in terms of total energy and environmental cost leaves a lot of room for improvement. A decrease of 50% in IG failure rate will have a very significant financial effect on the industry. The goal of improving IG durability by means of better testing and analysis is to reduce total costs through better control of the appropriate details of design, materials, and process.

The output of the simulation should be considered a guild to understanding IG durability in a comparative manner. The output is not an absolute statement of expected durability based on the input. As mentioned above, work remains to be done to advance the simulation. One area that commands a great deal of effort will be the task of validating the simulation tool. This process will occur at several different levels, from the material models up through correlating field failure data. This process will include response of the sub-models, testing current and developing assumptions, forcing root cause material and system failures as examples. The simulation responses must be collated to results from appropriately designed tests. Much of the testing that must be considered will be new protocols and associated procedures, for testing an assumption for example. In addition current durability and related protocols can be used for validation as they are correlated with the simulation response.

Although the current IG durability protocols and procedures provide an excellent base line for evaluating initial system integrity, when comparing the overall severity factors and material temperature data, the tests do not induce forces on the IG system in the same way or at the same level as would be expected over the required service life. Two areas of concern include:

Capturing fatigue failure which could result in catastrophic failure of the materials or their interfaces as well as gas loss, Capturing failures associated with the temperature and stress gradients revealed in the Cardinal experiment which could result in catastrophic failure of the materials or their interfaces as well as gas loss.

Adding to the systems based tests, sub system and materials test development must address current and future modeling assumptions.

In summary, the project has produced the first durability simulation tool of its kind and will provide an unquestionable advantage in supporting current and future IG design with its continued development. The tools can be utilized not only to guide the design processes but can also support physical test development and prioritization of research activities. Information, data and analysis contributed or generated in the insulating glass knowledge base has already provided insight supporting recommendations for actions that can:

- Have an immediate impact on IG duality through continued and expanded process quality and documentation
- Support review and validation of current modeling and IG design assumptions
- Support review and advancement of applied stress, stress gradients and fatigue application
- Support review and advancement of durability test protocol and procedure

7.0 Conclusions and Recommendations

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Based on learning experiences and developments in the project, the following conclusions and recommendations are made.

7.1 IG Durability Improvements, Current Production

The insulating glass manufacturer should insure, working up and down the fenestration value chain in a collaborative fashion, development of an IG product and engineering specification for the products they produce. (An example specification format is presented in Appendix 9) The more comprehensive, the more beneficial the documents are in supporting all aspects of the manufacturing process, including its control. These documents include metrics which can be chosen for monitoring and measuring; creating process validation nodes throughout the manufacturing processes as appropriate. Material specifications, engineering specifications, and process specifications are some of the keys to consistent quality in a product. During initial design of an IG unit, testing of the product is conducted to verify that the specifications are correct and that the specifications describe the product that is desired. The specifications are the tool used by a manufacturer to technically describe the product and to show that the product is intended to be of the described quality.

Quality processes should be implemented at all appropriate levels of all IG unit design and processing, supported by appropriate documentation defining successful implementation and its tolerance. Initially, each activity from incoming material to shipment should be characterized. This process will help define what activities are less than robust and need more attention for error detection, training, etc. More robust processes will take less attention. The robustness of a process is an attribute of the product design, the materials in the processes and the process design itself. Thus, less robust processes that are deemed out of control, uncontrollable or require expensive detection monitoring can be addressed through design and / or material change as well as process improvements. Consider that a sound, comprehensive quality process implementation insures a successful, consistent execution of design, material and process, thus, successful "certification" is the validation of that quality process.

There are several industrial organizations including IGMA, AAMA and GANA which can be leveraged to assist in defining and implementing quality assurance processes. These organizations have assembled quality manuals which provide guidance as well as training programs. In addition, the supply chain and customer base can contribute to a successful quality plan with similar documentation and training. The quality process which is implemented in any one manufacturing process is unique to that process; based on the choices of product and business requirements.

Most quality processes suggest training of manufacturing associates in quality activities. An important aspect of that training should include discussions which give the associates a clear understanding of the need to adhere to supplier recommendations for material handling. In addition to human safety considerations, an understanding of "protecting" the materials from contamination and why can be integrated throughout the assembly process. All materials in the IG, or that come in contact with materials in the IG, must have specifications that describe all aspects of the materials that may affect the product service life. Contamination of materials, either through their internal structure, or by surface contact may have severe consequences on IG life. One example of often overlooked contamination is the use of silicone hand creams or lotions by employees. The silicone may contaminate surfaces where adhesion of sealants is required. These surface contaminations, just as any raw material contamination of sealants during manufacturer, can have adverse effects on product service life.

The most current field studies as well as laboratory data suggests approximately 10% of IG assemblies fail within the first 10 years of service and that these failures are most commonly attributed to process failures. With documented product, engineering and process specifications and assuring consistent design and manufacturing execution, field failure rates will be improved.

7.2 IG Durability Simulation Design Tool, Validation

Validating the simulation tool will be an important aspect of continuing the tool development process. Facilitating the use of the tool and its acceptance requires that the validation process be an immediate priority. The importance of tool validation cannot be understated. We know that the model is built upon an understanding of the physical forces that are acting upon an IG unit and the IG unit's response to those stressors. Assumptions were made with respect to the boundary conditions for the model. Changes in these parameters could change the outcome of a simulation; therefore the output of model must be validated.

Validation will occur at several levels of the program and a well designed process will advance current understanding of IG durability in the near future. The new understanding can then be implemented in current and new IG designs, improving durability.

At the materials level, validation will be supported by tests designed to address material properties as they relate to long term exposure to the environmental stress as well as all levels of process variability. The test development and results along with continually advancing field data can then begin the model correlation process. Considering the current version of the simulation program, prioritization and planning should be given to validate, advance and build confidence in the:

- thermal, stress and permeation models
    - individually and coupled performance

    - boundary conditions
    - application of current assumptions
    - revise users manual as required to reflect needed understandings and model advancement
- current designs input and configurations
    - finalize execution and output on current (two) designs
    - revise users manual as required to reflect needed understandings and model advancement
- materials database
    - continue population of the database
    - execute material testing as required
- IG systems testing
    - develop model input representative of current durability testing stressors, execute for correlation using existing response data and forced failure data (if required)
- Field Data Collection,
    - develop a cooperative process for collection of contributed field service life data and field failure data
    - develop a cooperative process for collection of contributed certification (laboratory) results data

Model validation will continue as the model continues to advance.

7.3 IG Durability Simulation Design Tool, Current Implementation

In coordination with validation activities, the current simulation tool should be used to support understanding and prioritization of IG research.

Sensitivity Analysis

The current output options of the simulation let the user extract data at several levels. Varying input variables such as material properties and their variance or inputting "virtual" material properties will provide insight and direction for priority characteristics affecting IG durability. Sensitivity can also be run around application conditions, design parameters, etc. In addition, purposeful manipulation of input variables will provide similar insights to quality or process variance effects on durability.

Testing Protocol Analysis

Development and input data representing laboratory induced stressors with correlation to IG results can be leveraged for both simulation tool validation as well as advancement of the physical testing protocols and procedures.

7.4 Durability Simulation Design Tool, Continued Development

As has been discussed, the current version of the durability tool provides a solid foundation for the continuing development and completion of a comprehensive computer based IG design support tool. The completed tool will give the IG designer insight to 10, 20 or more years of their product service life in a matter of a few hours or less. Many recommendations for continuing development of the simulation tool have already be presented and discussed in preceding sections. Section 4.9.2 provides additional recommendations to advance the current version and discusses recommendations to advance simulation through the current time-step based methods to include predictive analysis that results in identification of the most likely system failure root cause. The importance of these recommendations centers on the result of the advancements, realizing there may be several methodologies and paths to consider in the process. As the development process continues, it is recommended that the following items be considered:

As presented here, the durability tool includes only two currently manufactured IG design configurations. The tool will accept dimensional changes, material changes, etc., but the relative positions or configuration of the IG systems can not be changed. The fundamental models used for the thermal, stress and permeation models are acceptable with consideration given to the simplifications and assumptions employed in the methodology. With the implementation of the additional IG designs, the fundamental models, their coupling and assumptions should be reconsidered for appropriate application. For example, the most commonly manufactured designs all include a gas filled air space between the glass lites. If the space was filled with an innovative insulating material there are several heat transfer and temperature issues which would need modification, the current models and assumptions would not be valid. An additional example would be the implementation of the three-glass lite designs, creating two gas filled volumes which are being sold for far northern applications.

Defined as an IG design and development tool, the program will inherently need flexibility in accepting input representing novel designs. Each novel application requiring a durability response will need to consider the validity in applying the algorithms as they exist at that time. Any inadequacy can be addressed with modification. The mathematical algorithms must be checked against the new system and adjustments, replacement or additions in the algorithms might be necessary to accurately describe and model the new system. It is envisioned, that at some point in its development, a library of algorithms, descriptions of usage and application will be made available. The algorithms chosen for a new or specific design analysis would then automatically develop their coupling attributes at the time of selection. Thus, more design iterations can be explored more quickly.

In addition to the specific IG geometry updates, sash applications need to be addressed. The current version provides a sash and sash interface geometry that is simple and straight forward providing the ability for material changes. The assembly interface is the “wet” seal glazing design with no options. The current version calculates expected temperatures of the sash material, its 1D expansion response and applies the expected force of the thermal deformation to the IG assembly through the glazing material. As presented in the preceding discussions, the following issues must be reconsidered in the future while applying the IG to existing and new sash designs.

The majority of current IG manufacturing is not well represented by an assembly in which wet seal glazing is applied to both the inside and outside as the primary seal and structural support elements. More common constructions / designs need to be implemented.

Window and IG manufacturers almost universally require "setting" blocks be used in the IG / sash assembly. Generally these blocks are intended to support all glass lites of the IG, removing the stress that would be associated with one supported lite and gravity continually acting on the other; creating a constant and continuing shear on the IG sealant.

Data has been presented that requires rethinking the assumptions associated with the thermal model. Considering the sash contribution to the system, the temperature of IG components is dependent on the sash material including its surface absorption characteristics, as the field data shows. Thus, as the model advances the recommendation for revision of the thermal model must include its extension to capture conduction, thus recognizing the sash's thermal effects on the system.

In the sections referenced above, recommendations are made directing advancement of the program including the current thermal model. In addition to those previously presented and the thermal model consideration of the sash as a thermal and mechanical stress input to the IG system, the following additional model recommendations are made for future revisions.

The current simulation does not consider diffuse radiation as an element in temperature calculation. The model needs to be revised to consider the daytime diffuse radiation component as well as the current direct component.

Field data presented in section 4.5.4 provides insight into the daily IG temperature cycling. The data clearly displays the gradients and their dynamic characteristic as the sun moves across the sky. The data also shows the magnitude of the temperature differences recorded throughout the system at moments in time. Advancement of the durability simulation must consider the material temperatures in a more realistic way. Many of the material properties which can affect IG durability are dependent on material temperature. The current assumptions (estimation of seal temperatures) are not adequate to cover the seal temperatures the data clearly demonstrates are possible in the continually cycling system (as an example). It is also recommended that existence of the temperature gradients and their attributes be explored relative to any possible contribution to an identified failure mode or an additional failure mode of the system. The simulation assumption (either IG cavity air temperature or the average of the temperatures of surfaces 2 and 3) of the seal temperature can be 20 degrees C below the actual measured temperature of the seal. This would translate into a difference in permeation rate change error of as much as 100% or more with a specific and possible set of conditions.

The process of capturing these temperature attributes in the thermal model will require advancing the model to 2D / 3D sophistication. These material temperatures provide the input to then capture and appropriately apply the thermal stress and strains exhibited in the system.

Recommendations for advancing the structural model are presented in 4.9.2. Those recommendations previously presented are focused on advancing the model capability to the more realistic 2D and 3D response. The following recommendations are examples intended to more specifically describe areas of the system that will be better represented with the more sophisticated models providing insight to their possible contribution to IG failure.

It is well known that the glass lites cycle through deformation from parallel based on temperature and pressure changes throughout their expected life. The current 1D and 1 ½ D models are not adequate to describe the full deformation of the center of the glass or the physical response of the corner sections of the IG panels. Implementation of 2 D, 2 ½ D and 3D models will provide the needed level of resolution to related these responses to failure modes and add to the overall understanding of IG durability.

The importance of describing, documenting and controlling the processing of material, material application , IG assembly, etc. as they relate to IG durability has been discussed in several areas. The current version of the simulation contains only limited abilities to explore expected assembly process variance. Additional insights can be obtained around process and quality issues through a purposeful manipulation of material properties. For, example, in a very known and controlled way, the adhesive strength (property) of a sealant can be manipulated as part of the simulation input to model the affect of dirty glass. The expected simulation output of such a process will only give a general trend of increasing or decreasing failure rates. The magnitude of the change in failure rates would be tenuously acceptable at best. It is recommended that the simulation be advanced to include the processes and their variances.

Considering that modeling the assembly processes is dependent on choices made in support of a set of product and business opportunities, as discussed earlier, the inclusion of process and quality modeling will be unique if very accurate results are required. The implementation of process and quality can be done at several levels of resolution, each delivering a parallel level of resolution in the results. The first Phase of implementation is recommended to leverage commonly used and known mathematical distributions representing the composite of the manufacturing processes. Ultimately, each step in the assembly process is characterized and implemented as individual distributions, or each individual distribution is used to create a compost distribution; then these factors are input to the simulation program.

In consideration of variance, just as acceptable tolerance (designed variance) is expected and documented on a part drawing, there is expected variance in each manufacturing process. The design of product and manufacturing processes understands and includes acceptable, validated variance in the design process. The final implementation of material variance and process variance will give the designer the ability to investigate effects of producing product on the low and high end of those variances on the overall durability of the product. This investigation assumes that all the processes (material processing, assembly processing, etc.) are under control just as is done in the current simulation. In other words, a consistent, quality product is being produced. If interested, the IG designer then could explore IG durability relative to processing that violates the designed variance. This can be defined as the effect of IG durability due to unacceptable quality or producing IG outside the documented product, engineering and / or process specifications.

7.5 Test Protocols and Procedures

The following recommendations for physical testing encompass both advancement of IG system and IG component durability testing. This testing should address validation of the simulation model, material property testing, investigation of current modeling assumptions and general understanding of root cause failure modes. Throughout the report, physical testing has been discussed in support of all of these tasks as well as advancement of current and future certification and building code programs. In general, the following discussion extends the presentation in section 5.3.2.

1. **Pressure Characterization Test**

   The test would place IG units in a pressure test vessel and cycle the units from room ambient conditions to plus and minus 2.5 psi, at 70 F constant temperatures. Center of glass thickness would be measured. When the center of glass thickness equals the edge thickness, the equivalent manufacturing conditions would be met under controlled conditions. This would quantify the varying barometric pressure and plant temperatures at which the IG unit was sealed. Center of glass thickness at some specified conditions above and below the sealing value would give data on the rigidity of the sealant and spacer assembly.

- Failure Modes Addressed
    - Sealant stress derived as a function of glass deflection
    - Deflection of glass in the IG assembly
    - Built in stress as a function of temperature, humidity, and altitude at the time the IG was assembled
- What the test will specifically reveal in terms of strength or a stress.
    - Strain in sealant and spacer section
    - Stress in glass lites
- Agreement on what the inputs (magnitude, duration, frequency, etc.) that should be imparted on the sample (IG / component)
    - Pressure range equivalent to change in altitude of +/- 2000 feet
    - Pressure range equivalent to temperature range of -30 degrees F to 140 degrees F
- How the procedures should be run to best model the "real" inputs and the responses to those inputs
    - This is a limited cycle test to characterize the unit exposure to pressure
    - Repeated test conditions should produce the same results.
    - Changed results indicate overstress of components and potential failure
- What modes should be perturbed?
    - Pressure changes at constant temperature
    - Varying fixed temperatures with repeated pressure changes
- Recommendations that will validate the stress inputs

    - Units now installed at elevation ranges over 1000-ft difference from the assembly manufacturing location
    - No control on temperature and barometric pressure at IG unit assembly
- Required strengths (responses)
    - Component level
        - No sealant fracture or separation
    - IG level
        - No failure of seal integrity
        - Change in response indicates IG process variation or material change
    - Certification level.
        - Failure here will also indicate a failure to achieve certification

Purpose:
To give a valid picture of the stiffness and deflection properties of the IG design. Various sealant and spacer designs would be expected to give different results. When a given IG design is characterized, repeating this test may give confirmation that the IG assembly process results in the same IG characteristics over a period of time and process variation has not occurred.

2. Pressure Cycling test

IG units would be placed in a pressure chamber and pressure cycled. The pressure limits may be based on the geographical location of typical installation locations as determined by the severity calculations previously described. Number of cycles would be representative of the desired lifetime of the unit. Temperature conditions could be varied from low to high, keeping in mind the total severity condition being applied to the unit.

- Failure modes addressed
    - Sealant fatigue failure during service life
    - Wear-out failure from normal service life internal pressure changes
- What the test will be specifically revealing in terms of a strength or stress.
    - Failed unit will leak moisture into the cavity and experience abnormal pressure changes
- Agreement on what the inputs (magnitude, duration, frequency, etc.) that should be imparted on the sample (IG / component)
    - Magnitude based on environmental conditions at the installation site
    - Number of cycles based on desired service life (20 years equals about 7300 daily cycles)
    - Cycle frequency based on acceleration factor desired
- How the procedures should be run to best model the "real" inputs and the responses to those inputs
    - Pressure cycling equal deviation above and below ambient pressure
    - Compensation for bias due to manufacturing temperature and altitude
- What modes should be perturbed?
    - Pressure; moderate temperature control to control test bias
- Recommendations that will validate the stress inputs
    - Observation of environmental conditions
    - Relationship to other accelerated testing where speed of pressure changes is less than 3 time constants of the unit response to applied stress change
- Required strengths (responses)
    - Component level
        - Must pass cycle test

- IG level
  - Must pass cycle test for verification of acceptable reliability and liability
- Certification level.
  - This test is far above the current requirements for certification
  - New certification tests for durable and predictable service life are expected

Purpose:

This is a dynamic cycling test to simulate changing internal/external pressure ratios caused by changes in temperature and barometric pressure. This would be designed as an accelerated wear-out type of test where the cycling rate is much faster than actual field temperature changes. This protocol will stress the adhesive through the same dimensional range that actual field units can see. This test can also be conducted at various temperatures to determine the effect of temperature on the sealant characteristics. Care must be taken to avoid overstressing the sealant. (Note 1 applies)

3. Temperature Differential Test

IG units would be placed in a fixture that allows a hot and cold water spray to be applied to each side of the assembly. After a period of time to stabilize, the hot and cold sprays would be reversed. This test is to stress the glass and adjacent seal in shear due to the thermal coefficient of expansion of the glass. Number of cycles should be appropriate for the installation location, as would be the temperature settings. Acceleration of the test results would be from a high number of short-term cycles (each cycle would be approximately 3X the thermal time constant of the IG unit). For a 9.75 inch sample length, the change in length for a temperature range of 0 F to 140 F is: 0.0107 inch for glass; 0.0277 inch for aluminum; 0.0198 inch for stainless steel; and 0.0136 inch for steel. These values place a substantial shear stress and elongation on the sealant.

- Failure modes addressed
    - Shear failure of sealant
- What the test will be specifically revealing in terms of strength or a stress
    - Ability of IG system to withstand differential temperature cycling, indoor vs. outdoor
- Agreement on what the inputs (magnitude, duration, frequency, etc.) that should be imparted on the sample (IG / component)
    - Temperature range from above freezing (for water spray) to about 110 F for maximum temperature
        - Thermal time constant needs to be determined for the IG in the water spray at temperature T2 (T1 = starting temperature, T 2 = ending temperature)
- How the procedures should be run to best model the "real" inputs and the responses to those inputs
    - Cycling rate 3 thermal time constants for each change in temperature
    - Number of cycles per weather/environment conditions for location
    - Test duration limited to 2 months with periodic checks of seal integrity
- What modes should be perturbed?
    - Min and max temperature
        - Water coverage and rate (will change thermal time constant of IG test)
- Recommendations that will validate the stress inputs
    - Measurement of dimensional changes during cycling
    - Measurement of average cavity temperature
    - Correlation to field service life. (See note 1)

- Required strengths (responses)
    - Component level
        - Durability of sealant adhesion and cohesive strengths
    - IG level
        - Must pass the final test procedure to qualify as meeting expected durability/liability
    - Certification level.
        - No correlation to present IG certification level
        - Future IG durability certification will include this test

4. Twist (torsion) Cycling Test

This test would subject IG units to a twisting force similar to that seen in casement style windows during operation. A torsional force may also be applied to some units from their installation in a building when the window unit is forced into alignment with a wall surface. The torsional stress causes a high shear stress in the sealant. A measurement on the torsional stiffness of an IG will give data on the sealant system rigidity. The test parameters would be based on the shear stress allowed in the sealant material specification. Test rate and number of cycles is to be determined.

- Failure modes addressed
    - Shear stress in sealant
    - Durability in casement window applications where twisting of sash occurs
    - Torsional stiffness will be a measure of IG design parameters
- What the test will be specifically revealing in terms of a strength or a stress
    - Change in torsional stiffness indicates a change in materials or process
- Agreement on what the inputs (magnitude, duration, frequency, etc.) that should be imparted on the sample (IG / component)

    - Torsional deflection limited to maximum shear stress of sealant in the material specification
    - Torsional deflection limited to the angular deflection found in specified sash (this will vary by window manufacturer)
    - Number of cycles related to specified service life operational cycles.
    - Magnitude of severity overstress (safety factor) to be determined (See note 1)

- How the procedures should be run to best model the "real" inputs and the responses to those inputs
    - Angular deflection controlled to the stress levels specified
    - Cycling rate of 1 minute per full cycle (equal deviation from flat surface condition).
- What modes should be perturbed?
    - Angular deflection, cycling rate, ambient temperature
- Recommendations that will validate the stress inputs
    - See note 1
- Required strengths (responses)
    - Component level
        - No sealant failure of IG leakage failure
    - IG level
        - Must pass engineering specification ratings for windows
        - Must pass engineering specification for IG handling at window assembly and building installation.
    - Certification level.
        - Not covered in present certification programs

        - Needs to be addressed in durability certification for casement window applications and other operator types, i.e., awning windows

5. Static Shear and Creep Test

In this test one of the lites in the IG unit would be supported and the other lite unsupported. A load would be applied to the unsupported lite sufficient to place the sealant materials near the shear stress allowed in the sealant material specification. Measurement of the amount of movement of the unsupported lite gives the creep of the sealant after a period of time. In this test, as well as in the other tests described in this section, the temperature at which the test is run needs to be determined.

- Failure modes addressed
    - Long term shear loading and stress when both lites may not be properly supported
- What the test will be specifically revealing in terms of strength or a stress.
    - Movement of unsupported lite and resultant failure of sealant system
    - Will clarify need for and specification limits regarding equal support of glass lites
- Agreement on what the inputs (magnitude, duration, frequency, etc.) that should be imparted on the sample (IG / component)
    - Force on unsupported lite equal to 2 times glass weight
    - Time duration 1 month
    - Ambient temperature
    - Measurement of glass movement
- How the procedures should be run to best model the "real" inputs and the responses to those inputs

    - One edge of one lite supported on firm, fixed stable base, other lite subject to applied weight equal to glass weight evenly distributed along entire top edge. IG held in upright vertical position, Initial and periodic measurement of unsupported lite movement

- What modes should be perturbed?
    - Magnitude of applied force
    - Ambient temperature
- Recommendations that will validate the stress inputs
    - Observation of present glazing practices and support of both lites by the sash frame
    - Present alignment measurements of both lites in current IG manufacturing
- Required strengths (responses)
    - Component level
        - Shear strength of sealant in relation to glass weight
    - IG level
        - Proper alignment of bottom edge of both lites of glass
    - Certification level
        - Present certification does not address glass lite alignment, setting blocks are assumed to cure misalignment

6. Temperature Cycling Test

In this test the entire IG would be placed in an immersion type chamber and the temperature cycled. Number of cycles and temperature extremes needs to be determined.

- Failure modes addressed

- Sealant adhesion and cohesive strength
- Environmental cycling stress on sealant due to temperature and deflection

- What the test will be specifically revealing in terms of a strength or stress.
  - Properly specified and processed IG will withstand the environmental stress with an adequate durability and reliability index.
- Agreement on what the inputs (magnitude, duration, frequency, etc.) that should be imparted on the sample (IG / component)
  - Certain manufacturers use this test method for internal testing
  - Temperatures and cycling rates need to be determined.
- How the procedures should be run to best model the "real" inputs and the responses to those inputs
  - Units to be checked for seal integrity before, during, and after cycling.
  - Cycling rate to be less than 3 times the thermal time constant of the IG units tested.
- What modes should be perturbed?
  - Temperature min and max
  - Cycling rate
- Recommendations that will validate the stress inputs
  - Confirmation by present users of this test procedure
  - Environmental conditions during the expected life of an IG unit
- Required strengths (responses)
  - Component level
    - Must pass this test
  - IG level
    - Must pass this test to demonstrate required durability

- Certification level
    - Not present in current certification procedures
    - Recommended to be included in durability certification procedure

7. Sealant UV Exposure

Sealant applied to test strips of glass 1 x 3 inches would be exposed to UV light and moisture for a period of time. The force needed to pull the glass test strips from the sealant would be measured. The modulus of the sealant also would be checked for changes during the test.

- Failure modes addressed
    - Adhesive failure of sealant to glass and to spacer
    - Degradation of sealant material with exposure to UV in sunlight
- What the test will be specifically revealing in terms of a strength or stress.
    - Loss of adhesion with UV and/or moisture
    - Change in sealant properties with UV and/or moisture
- Agreement on what the inputs (magnitude, duration, frequency, etc.) that should be imparted on the sample (IG / component)
    - UV intensity to be determined, samples will be exposed to UV both directly and through the glass
    - Duration expected to be 30 days with visual observations more frequently
- How the procedures should be run to best model the "real" inputs and the responses to those inputs
    - Sample pieces randomly piled in pan of water 6 to 12 inches below UV lamps
    - Sample pieces to have random orientation so all types of exposure exist.

    - Test to be at ambient room temperature

- What modes should be perturbed?
    - UV light intensity
    - Cleanliness of glass surfaces
    - Process values in attaching sealant to glass
- Recommendations that will validate the stress inputs
    - This test has been observed in labs of sealant manufacturers
- Required strengths (responses)
    - Component level
        - Sample to retain adhesion throughout test
        - Sealant to maintain material specification properties
    - IG level
        - Failure during this test indicates future failures in IG units
    - Certification level
        - Not in present certification programs.
            - (Test is in the realm of material testing)

8. Interior IG Dew Point

An improved method of measuring the interior dew point is needed. The existing method uses a fixed temperature cup and takes a significant amount of time to equalize and determine whether moisture is present on the inside of the glass. If the reading needs to be repeated for another temperature, the total test time is very long. A new method of using a test probe with a decreasing temperature ramp would speed up accurate dew point readings. Another method worth further development would be a dew point sensor sealed inside the IG unit.

- Failure modes addressed
    - Increase in interior dew point during IG life
- What the test will be specifically revealing in terms of a strength or a stress
    - Rapid response during test and real value of dew point
    - Presently is a pass/fail test and takes a long time to retry at different dew points
- Agreement on what the inputs (magnitude, duration, frequency, etc.) that should be imparted on the sample (IG / component)
    - Correlation of test method with present ASTM and European methods
- How the procedures should be run to best model the "real" inputs and the responses to those inputs
    - Test method to be developed. Lab in Canada has worked on this with good results in field testing
- What modes should be perturbed?
    - None
    - Development of test method is to result in a consistent procedure.
- Recommendations that will validate the stress inputs
    - Correlation of test method with present ASTM and European methods
- Required strengths (responses)
    - Component level
    - IG level
        - Rapid exact results
    - Certification level
        - Will speed up certification testing

9. Material Tests

These tests will be specifically designed to provide insight to if and to what magnitude process variance has on IG durability. The tests will span processes from the basic materials level through the processes of IG assembly where variance can occur. The tests would include the following as examples.

  - Glass cleanliness
  - Edge deletion quality
  - Spacer leak rate, dependent on spacer design (Roll formed spacers may contain microscopic fractures at sharp longitudinal bends.)
  - Sealant viscosity, modulus, adhesion, elongation, shear strength, tensile strength, composition, permeation rate under stress, and other characteristics
  - Desiccant absorption, desorption, capacity
  - Spacer surface finish, contamination, and sealant adhesion test
  - Other tests

- Failure modes addressed (See detail above)
  - Sealant adhesion
  - Moisture penetration of sealant
  - Desiccant properties and capacity
  - Spacer adhesion, breathing, and barrier properties
  - (etc)
- What the test will be specifically revealing in terms of a strength or a stress
  - Adhesion of sealant to glass and spacer
  - Desiccant capacity
  - (etc)

- Agreement on what the inputs (magnitude, duration, frequency, etc.) that should be imparted on the sample (IG / component)
    - Details to be covered by values in the material specification and piece part prints
- How the procedures should be run to best model the "real" inputs and the responses to those inputs
    - Details to be covered by values in the material specification and piece part prints
- What modes should be perturbed?
    - Test methods should follow ASTM and other standards to give consistent results
- Recommendations that will validate the stress inputs
    - ASTM and European material standards with emphasis on IG application
- Required strengths (responses)
    - Component level
        - Must meet engineering specifications
        - Failure or variance will hinder durability of IG units
    - IG level
        - Out of specification values unacceptable for certified and warranted units
    - Certification level
        - Present certification does not address this situation except in Europe (EN-1279)

10. High Humidity Soak Test

Placing units in a heated pressure chamber where the vapor pressure can be raised and the pressure counteracts the deflection of the glass caused by the test temperature would enable a more severe high humidity test without otherwise affecting the test unit. When the temperature is raised to 180 F @ 95% RH the vapor pressure raises to 7.298 psi. With an increase in pressure of 1.525 psi., the deflection of the glass will be near zero and the sealant unstressed mechanically. This will allow 184.4 vapor pressure psi- hrs per day test exposure for a 10-year equivalent of 182 days for the most severe actual exposure. A realistic 10-year test of a moderate climate humidity exposure such as Minneapolis could be run in as little as 61 days.

- Failure modes addressed
  - Moisture penetration of sealant system
  - Fogging of IG
  - Internal IG condensation
- What the test will be specifically revealing in terms of strength or a stress
  - Ability of the IG to withstand environmental humidity exposure
- Agreement on what the inputs (magnitude, duration, frequency, etc.) that should be imparted on the sample (IG / component)
  - Weather data for installation locations gives the practical values for testing
  - Extended humidity exposure increases failure rate of IG units
- How the procedures should be run to best model the "real" inputs and the responses to those inputs
  - High humidity test chambers
  - Testing under increased pressure to increase moisture severity and decrease test time.
- What modes should be perturbed?

    - Test duration
    - Temperature
    - Pressure to increase permeation stress without increasing mechanical sealant stress
- Recommendations that will validate the stress inputs
    - Study of weather data for various locations
- Required strengths (responses)
    - Component level
        - Not directly applicable
    - IG level
        - Durable and reliable IG units must meet this test
    - Certification level
        - Present certification does cover humidity testing at a lesser level than actual exposure. Different locations have differing humidity severity exposures.

11. Impact Test

One lite of an IG would be mounted vertically in a rigid frame which moves in a vertical direction. The other lite is unsupported. The frame is raised and allowed to drop vertically onto a heavy base. The resulting shock would be similar to that experienced by a double hung window sash which drops or is slammed closed. Number of cycles and the test temperature needs to be determined.

- Failure modes addressed
    - Shear failure of sealant, adhesive and cohesive
- What the test will be specifically revealing in terms of strength or a stress.
    - Ability of IG to meet operating conditions in operable hung sash

    - Ability of IG to meet long term durability when both lites are not equally supported
- Agreement on what the inputs (magnitude, duration, frequency, etc.) that should be imparted on the sample (IG / component)
    - Some IG manufacturers have conducted a similar test for their materials and design.
    - Details of previous tests not well documented in public literature
- How the procedures should be run to best model the "real" inputs and the responses to those inputs
    - Force levels and drop distances to be modeled after weights and other details of actual windows.
    - Cycling rate on number of cycles to be representative of actual field usage expectation
- What modes should be perturbed?
    - Drop distance
    - Drop surface stiffness and shock absorbing characteristics.

- Recommendations that will validate the stress inputs
    - Possible confirmation of testing by manufacturers that have conducted these tests
- Required strengths (responses)
    - Component level
        - Will verify adhesive and cohesive strength levels of sealant
    - IG level
        - Must pass dew point testing after this test
        - Must pass long term exposure after this test

- Certification level
  - Not covered in present certification test programs

In development of these and other new test procedures, it will be imperative that each and every test be quantified with actual field experience. During this development process, new and additional test procedures will become evident. Refinement of test details will enable the new tests to more closely correlate with field exposure. An important aspect of this testing will be the failures produced. Failures during testing enable accurate identification of failure causes and the knowledge to improve the quality of IG units. Failures are also required to produce statistically valid results.

Note 1 It is very important that new test standards be correlated with actual field experience. Details of field experience and clear data on field failures is not readily available. An important part of test development to improve IG durability is to conduct field studies that give clear detail of IG construction details and processing and also give clear details of the field installation conditions. Weather records during the field exposure give credence to the conditions experienced by the IG units.

Failures are expected during IG service lives. The failure rate is the critical value which increased durability is attempting to reduce. A good goal for development of new test standards is to reduce the failure rate to 1/2 that of the present rate.

Testing results are not very useful until failures occur. Improvements can only be made in IG materials and processing when problem areas are fixed or improved. Test methods are intended to produce failures at some point during the test. By studying the failures, changes in IG design and process can be made. Re-testing that reduces the failure rate demonstrates an improvement in reliability. Reliability calculations require failures to clearly show the true expected reliability and durability.

Appendix 1

Phase I Final Report

An Insulating Glass Knowledge Base

Phase I Final Report

DE-FC26-01NT41258

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Aspen would also like to acknowledge the multitude of industrial contributors whose participation was pivotal in the success of this effort.

Synopsis

This report will discuss issues relevant to Insulating Glass (IG) durability performance by presenting the observations and developed conclusions in a logical sequential format. This effort, covering Phase I activities, discusses a qualitative assessment of durability issues. The subsequent, Phase II, activities will be discussed in a future document which will focus on quantifying these durability issues.

An overview of typical IG constructions is provided. This overview includes identifications of representative design classes as well as descriptions of typical component characteristics. Potential system failures are captured for the identified constructions. The system failures occur due to failures of components or their interfaces. Failure Modes and Effect Analysis and Event Tree techniques are used to describe the potential system failures with respect to failure of the components and subsystems. A detailed qualitative discussion of component and interface failure modes is presented. Design and process issues which drive the failures are discussed. The underlying failure theory is also discussed.

The effect of environment on IG performance is discussed. Environmental parameters which directly correlate to system failure are discussed qualitatively. An example of how environmental parameters may be analytically captured is presented. A methodology for estimating the composite severity effects on an IG product, given a multitude of environmental factors is discussed.

Theoretical constructs for describing how environmental factors result in physical stress and failure of a system are presented. The constructs include analytical models describing the IG pressure-volume relationship, moisture vapor transmission, and gas permeability.

A reliability estimate of specific existing IG products is presented. The reliability predictions are derived from existing field service data. The results of the assessment are presented as well as the methodology followed. The methodology presented can be used as a template for future such analyses.

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1. Introduction

Richard Hage

1.1 The Need for An Insulating Glass Knowledge Base

The objective of the Insulated Glass Durability Knowledge Base, an effort funded by the U.S. Department of Energy (Cooperative Agreement DE-FC26-01NT41258), is to provide a mechanism by which durability characteristics of current IG units can be captured in a useful and practical manner. The effort will be performed by Aspen Research Corporation in conjunction with its partners in industry, academia, and government.

To fulfill the goals of this project, the knowledge base will consist of two primary structures: a durability evaluation tool and an IG design data repository. The durability evaluation tool will support the following analyses: material sensitivity, design sensitivity, environmental sensitivity, and durability performance predictions. The design knowledge repository will contain practical and useful design references: event tree diagrams for representative design classes, relevant material properties, regional environmental exposure levels, mechanistic failure models, and national and international standards relevant to IG product development and testing.

This paper discusses the structured methodology that will be followed for development of the durability evaluation tool. The methodology represents a structured approach founded upon sound reliability and mechanistic modeling principles.

1.2 Philosophical Approach

This project has been defined as a two-phase project. The first phase is intended to discuss Insulating Glass durability issues at a qualitative level. That is, the relevant issues will be identified, and technical understanding will be developed and communicated regarding these issues. For the first phase, the technical discussions will be focus on first principles theory and practical considerations. In most cases, numeric values will not be quantified for these statements, but the statements will support future, phase two, quantification of the first principles derived theory. This section discussed the overall approach taken to fulfill the requirements of this project.

One of the principal challenges of this reliability effort is development of durability assessments that are applicable to a wide variety of products. In addition to variations of material properties, significant design variations for different classes of products must also be addressed.

For example, two significantly different IG designs are shown below [1]. Figure 1-1 shows a common IG design, which involves a structural spacer, a primary sealant material, and a secondary sealant material. This schematic is a simplistic representation of this common IG design. The implementation of the design typically involves metals or polymers for the spacer. Another common IG design is shown in Figure 1-2. This design uses the sealants as the spacer. In both designs, the primary and secondary sealants are typically some of the following organic compounds: butyl (hot melt or not), polyurethanes, polysulfides, or silicone [2]. In addition to various classes of materials being used, there are also significant variations within the material classes due to formulation differences. When comparing these two designs, it is obvious that their durability response characteristic will not in general be identical. Rather, their failure mechanisms may differ substantially.

Failure Modes and Effects Analysis (FMEA) is the approach that will be used to capture understanding of how the failure mechanisms relate to system failure. The FMEA documents will form the initial basis for considering the durability similarities and differences between differing designs.

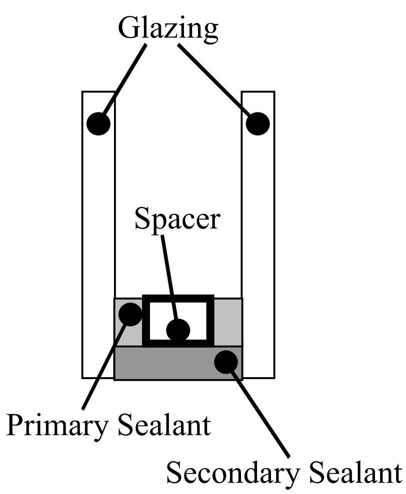

Figure 1-1. Common IG design with box spacer

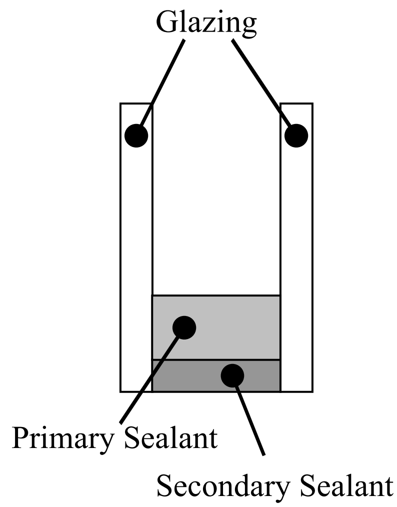

Figure 1-2. Alternative IG design

Event tree diagrams will be used as a tool to translate the verbal FMEA descriptions into mathematical constructs to describe system failure. The event tree approach is commonly used to capture the interaction of failure mechanisms for complex systems [3]. The event tree begins at the top level as a system that has not yet experienced failure. Paths from the initial unfailed state then progress along tracks of subsystem failure events until the end system result of either failure or success is achieved.

The event tree diagram must be developed uniquely for each identified class of design. An example event tree diagram, developed for the case of an IG with spacer design (represented in Figure 1-1) is shown in Figure 1-3. This event tree diagram is for illustration purposes only, and is not by any means intended as an official finalized diagram for describing this design's potential failures. When this effort is completed, however, there will be event tree diagrams developed for each relevant class of designs. The finalized event tree diagrams will be developed with input from industry, academia and government.

The event tree shown in Figure 1-3 begins with the state of an unfailed IG unit that has just begun its service life. Its durability performance over its lifetime is then modeled as a chain of potential failure events. Each link in the chain of potential failure events can be modeled as a flowchart decision block with the outcome of the event being either success or failure with respect to the stated mechanism. If the block fails due to its stated failure mechanism, the continuing failure chain is then evaluated to ascertain whether the chain of events will continue until system failure is realized. If failure does not occur, other failure mechanism chains are examined to see if they will result in failure. The flow continues until either system success or failure is ultimately realized.

The decision blocks in the event tree will be developed such that they each capture a unique failure mechanism, for example primary seal cohesive failure or primary seal adhesive failure. At this point it is important to develop a methodology for consistently assessing the individual decision blocks. To evaluate the decision blocks it is necessary to think of each potential failure in terms of the competing nature of stress and strength. The completed event trees will not only incorporate field induced stresses, but will also incorporate stresses and thus failure events corresponding to processing issues. The general methodology to treat each of the decision blocks is described in Figure 1-4, for the specific case of primary seal cohesive failure.

As is seen in the Figure, in order to evaluate the outcome of the decision block it is necessary to have the following four primary elements:

- relevant environmental parameter values
- relevant material property values
- a translating algorithm for converting environmental parameters to material stresses
- an algorithm for comparing the material stress values to its strength properties

To be the most useful, the environmental stress and material property data should capture not only the expected values of parameters, but also their probabilistically distributed nature. The translation step will involve mechanistic modeling of the failure mechanism in terms of the environmental stress. The outcome of the decision block will be a result based on the comparison of the translated stress and the defined material strength.

The procedure for evaluating event tree diagram decision blocks will be implemented in a consistent manner for each decision block, which is shown in Figure 1-5. When applied in such a consistent manner, the result will be two algorithms that are defined within each decision block: the environment to stress translation algorithm, and the stress to strength comparator algorithm. The stress translation algorithms, each unique to a design block, will draw data from the environmental database. Each translation algorithm will draw the environmental parameters from the environmental database, which are relevant to the mechanistic model [4]. The comparator algorithms will also be unique within each decision block. The comparators will draw material properties from the material property database, which are relevant for the material and stress value under consideration [5]. The environmental database will include information of all relevant environmental parameters and for all relevant environmental regions. The material property database will include information of all relevant material properties and parameters. The environmental data and material property data will be stored in terms of not only expected values, but also in terms of the probabilistic nature of the parameter values.

Once the event tree diagrams have been completed, with their embedded decision blocks and mechanistic models, they will then be evaluated. The event tree is driven by probabilistic events, due to variation in environmental stresses and due to variation in material property strengths. The system will thus be assessed by treating it as a stochastic process.

A variety of techniques can be used to develop durability statements from the resulting system model relationships. In the phase I effort, statements will be made using a model with relatively few system failure mode blocks. This more simplistic representation will provide some initial insight into perceived IG durability performance. In the phase II effort, more sophisticated analysis techniques will be used to make refined statements. The phase II quantified model inputs, with the validated mechanistic models, will allow Monte Carlo simulation techniques to be used to evaluate predicted durability performance.

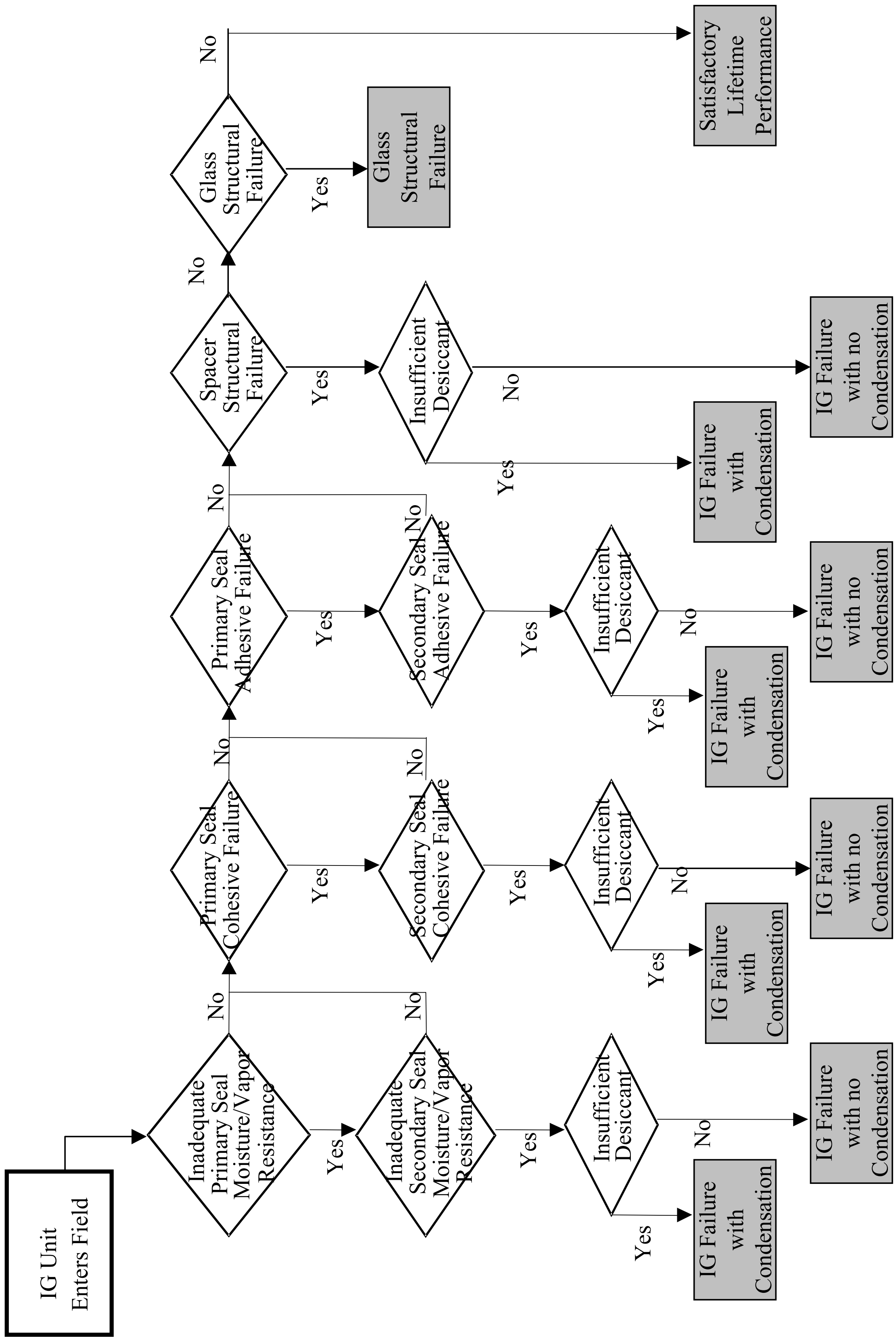

Figure 1-3. Event Tree Diagram Concept

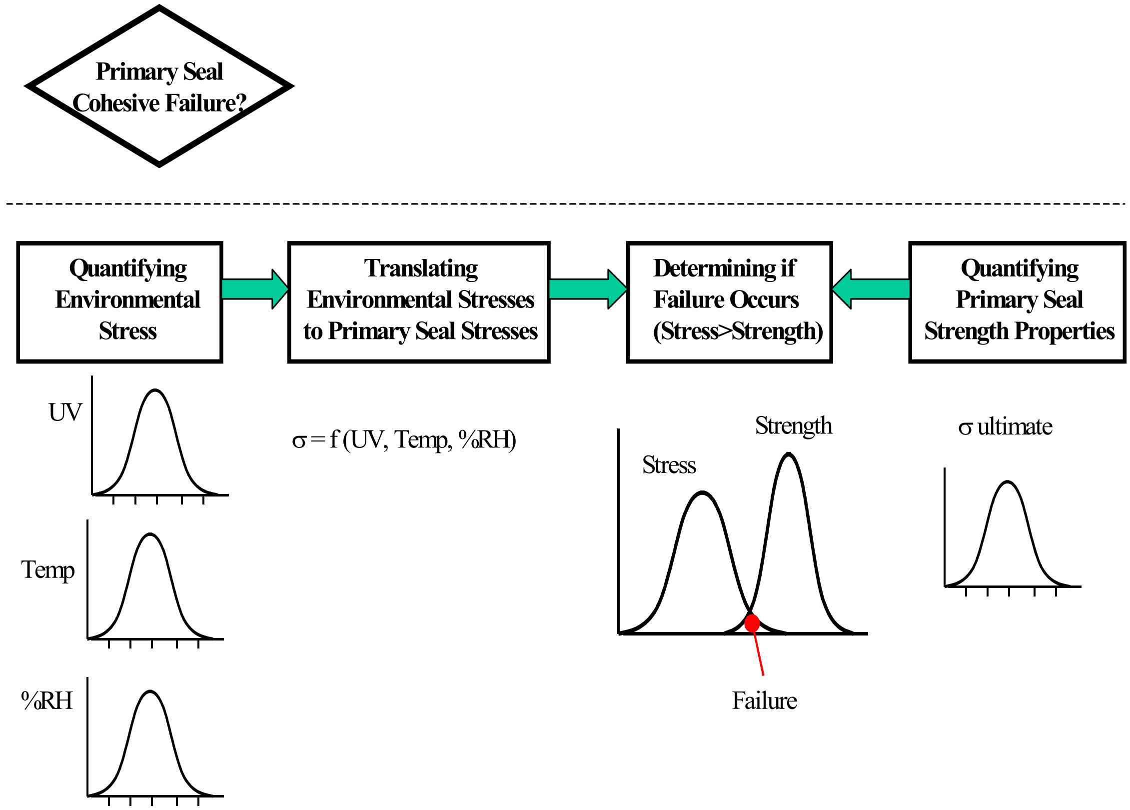

Figure 1-4. Methodology for Evaluating Event Tree Blocks

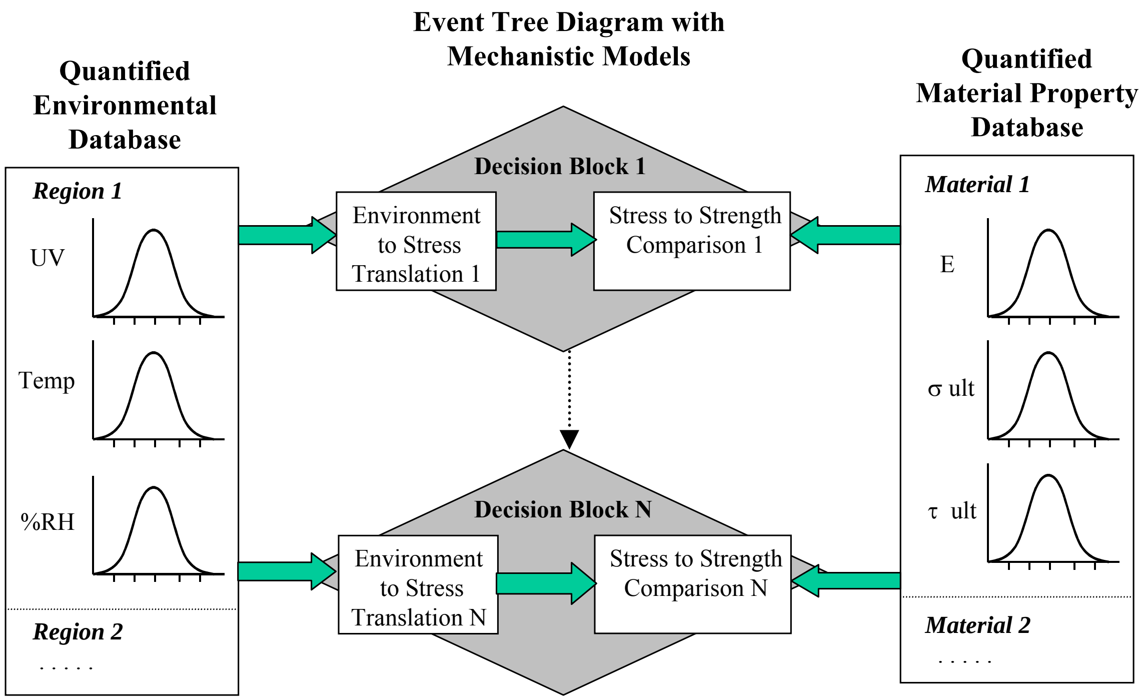

Figure 1-5. Generic Flow of Data for the Knowledge Base

The complete validated outcome of this effort will be a structured tool for IG durability evaluation. The tool will be useful for the following activities.

- Material sensitivity analyses
- Design sensitivity analyses
- Environmental sensitivity analyses
- Durability performance predictions for stated designs

This structured approach will result in the development of unique event tree diagrams for each class of IG design. The FMEAs generated will provide useful templates for understanding and guiding IG and spacer system design and production processes. Within each of these designs, inherent material and environmental variations dictate that a probabilistic approach be utilized. The necessity of converting environmental parameters into material stresses dictates that mechanistic failure models be developed and implemented.

The structured approach will result in a practical and meaningful IG design data repository. The following IG design knowledge will be captured:

- Failure Modes and Effects Analysis document for each IG design class
- Event tree diagrams for each IG design class
- Material properties for all relevant generic and specific IG material properties
- Relevant environmental exposure values
- Mechanistic models (translation algorithms) for defining material stress in terms of environmental parameters
- National and International standards for IG product development and testing

By rigorously following this methodology, it will be assured that all relevant failure mechanisms, environmental parameters, and material properties are addressed. In addition, interactions between the failure mechanisms will be captured and understood. In summary, following this structured approach will ensure that a useful and practical durability evaluation tool for the Insulated Glass Durability Knowledge Base is achieved.

Again, this report summarizes phase I of this activity, which was primarily involved with development of first principles qualitative understanding of IG durability. The phase II effort, which will focus on quantification is proposed for a following report.

1.3 Content of the Phase 1 Final Report

This report will attempt to discuss the relevant issues by presenting the developed phase I conclusions and observations in a logical sequential format.

Chapter 2 provides an overview of typical IG constructions. This overview includes identifications of representative design classes as well as descriptions of typical component characteristics.

Chapter 3 provides an overview of potential system failures. The system failures occur due to failures of components or their interfaces. Failure Modes and Effect Analysis and Event Tree techniques are used to describe the potential system failures with respect to failure of the components and subsystems.

Chapter 4 provides a detailed qualitative discussion of component and interface failure modes. Design and process issues which drive the failures are discussed. The underlying failure theory is also discussed.

Chapter 5 discusses the effect of environment on IG performance. Environmental parameters which directly correlate to system failure are discussed qualitatively. An example of how environmental parameters may be analytically captured is presented. A methodology for estimating the composite severity effects on an IG product, given a multitude of environmental factors is discussed.

Chapter 6 presents theoretical constructs for describing how environmental factors result in physical stress and failure of a system. The pressure-volume relationship, which directly correlates to sealant stress, is captured within a proposed model, which when validated may be useful for proactively estimating the flexure and sealant stresses of IG units. A model is presented for describing moisture vapor transmission through sealants. A model is also discussed for describing Argon loss due to sealant gas permeability.

Chapter 7 provides a reliability estimate of specific existing IG products. The reliability predictions are derived from existing field service data. The results of the assessment are presented as well as the methodology followed. The methodology presented can be used as a template for future such analyses.

The appendices contain a variety of useful relevant information. A summary of relevant ASTM test methods is presented. The complete technical monthly reports to the DOE are presented. Published reports presented to during the duration of the phase 1 activity are also presented in their entirety.

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2. Overview of Typical IG Constructions

Boris Rozynov, Gerald Hendrickson, Richard Hage

2.1 Representative IG Design Classes

The performance capabilities of Insulating Glass units have evolved as their enabling technologies have matured. The initial IG concept was to separate two panes of glass by a volume of air. This resulted in a significant benefit in energy performance. The enabling technology has since matured to allow improvements of both energy loss and heat gain through the use of coatings. Interior condensation is reduced by proper selections of desiccants and sealants. Energy performance is further increased by using inert gas in the interior void.

With the increased sophistication of the IG unit, and with its increased performance, the consumer's demands have also increased to a greater level of sophistication. From a homeowner's perspective, as customer, the following are common expectations regarding IG performance:

- Optimum U-value
- Optimum Solar Heat Gain Coefficient
- No internal condensation
- No glass cracks
- Seals house interior from outdoors

A goal of this documented effort is to communicate durability issues across the Insulating Glass industry. To be useful, the durability issues should be communicated relative to customer requirements. By discussing these issues, increased awareness of durability issues will support design and process choices which will allow increased durability performance of IG units. In order for this goal to be accomplished, it is desirable to discuss durability issues to a level of detail such that they are actionable items, rather than vague statements. In order for detailed statements to be made, it is necessary to discuss specific design attributes. There are a diversity of design solutions available, therefore it is necessary to discuss a broad base of design variations. In an attempt to capture a relatively comprehensive list of the design solutions available, an effort was made to identify a manageable number of core design classes. Each design class represents a grouping of design solutions which have common primary functional elements.

Within each design class there are also variations of materials and configuration geometries. Each IG design variation includes variations of both glass attributes and spacer system attributes. Glass attribute variations typically involve the following elements:

- Glass thickness
- Glass coating
- Glass heat treatment

IG units also vary by using different spacer systems. The spacer systems vary significantly with respect to design approaches chosen to achieve the customer requirements. Each spacer system type can support the glass attribute variations discussed. Since glass attributes are primarily dimension and material specific, and the spacer system has greater functional difference, the design classes are defined in terms of the differing spacer systems. The glass attributes are viewed as material and geometry differences within these identified design classes. Of the spacer system alternatives, five design classes were identified as nearly approaching a comprehensive listing of design solutions available to the consumer. Each of these identified design classes were assessed in qualitative detail during this effort.

The five design classes are as follows:

- Box Spacer System
- U Channel System
- Corrugated Metal Spacer System
- Non-rigid Barrier Spacer System
- Thermoplastic Spacer System

To achieve the previously stated customer requirements, each of the design classes must satisfy several functional requirements. Satisfactorily realizing these functional requirements will result in achievement of the customer perceived requirements. The required functional requirements are as follows:

- Connect the glass panes
- Maintain IG pane edge spacing
- Minimize water vapor transport
- Ensure dry interior
- Minimize gas permeability
- Optimize pane flexure
- Minimize thermal conductance

Each IG spacer system design is an attempt to satisfactorily address these required functions. In the following sections an attempt will be made to discuss how the various design classes address these issues. Each spacer system will now be discussed with the goal of describing the systems and identifying how each achieves each of these required functions.

Consider the box spacer system shown in Figure 2-1. A metal spacer provides the stiffness required for separating the panes. The moisture vapor transmission resistance (MVTR) sealant provides the barrier to moisture vapor transmission. Desiccant, contained within the spacer, traps the moisture that passes through the MVTR seal. The MVTR seal also provides resistance to gas permeation. The MVTR seal is typically butyl. The pane flexure is resisted by the entire MVTR seal, structural seal, and metal spacer configuration. The majority of the resistance comes from the structural seal, with the metal spacer acting as a fulcrum to the bending. The structural sealant has significantly higher modulus than the MVTR sealant. It is typically silicone, polysulphide, or polyurethane. A driving factor for the thermal transfer through the spacer system is the material and configuration of the box spacer. The thermal conductivity of the material, the wall thickness of the spacer, and the width of the spacer are important.

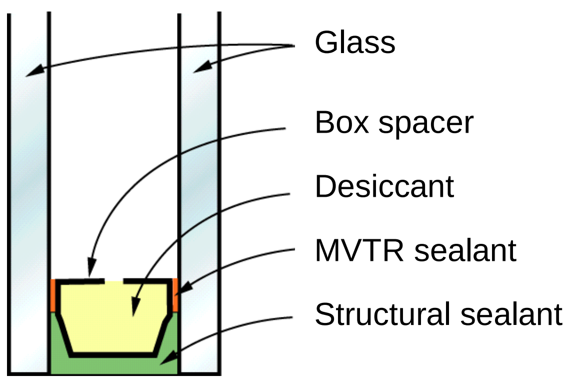

Figure 2-1. Box Spacer System

Figure 2-2 shows a U-channel spacer with dual seals. The MVTR seal provides the moisture vapor transmission resistance and gas permeability resistance. The structural seal provides flexure resistance. Using U-channel, however, allows the spacer to behave as a torsional spring and thus take up some of the flexure loading, while still maintaining significant compression rigidity. If optimized properly, the U-channel, which is typically a metal, could also result in a lower thermal conduction rate, due to the deceased cross section conduction path of the spacer metal. Also, by accommodating flexure within the U-channel, there will be less stress cycling of the MVTR sealant.

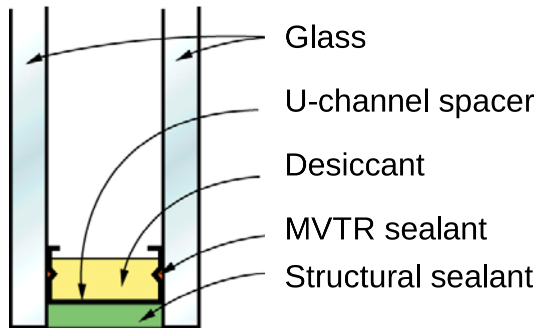

Figure 2-2. U-Channel Spacer System

Figure 2-3 shows the corrugated metal spacer design class. The pane spacing edge gap is maintained by a metal strip that is corrugated along its length. The corrugation provides a sufficient area moment of inertia to the strip to prevent both buckling and flexure. The metal strip also acts as a barrier to moisture transmission and gas permeability. Butyl sealant is on both sides of the corrugated strip. The sealant resists both moisture transmission and gas permeability that passes either through defects in the corrugated strip or around the edges of the strip. To resist flexure, the corrugated strip acts as a fulcrum. The butyl resists the torsion by tensioning and compressing on alternative sides of the strip. The butyl strip on the IG interior is constructed with desiccant, to dry the cavity. The thermal conductance is driven by the transfer through the butyl and the corrugated strip.

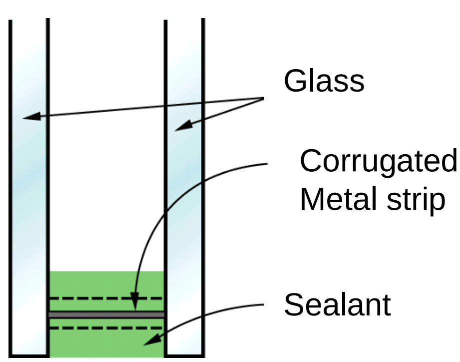

Figure 2-3. Corrugated Metal Spacer System

Figure 2-4 shows the non-rigid barrier spacer design class. In this system, the primary function of the structural sealant is maintaining the edge gap and resisting flexure, since its modulus and strength is typically sufficiently higher than that of the MVTR sealant. The structural sealant is within the interior of the IG. The structural sealant is impregnated with desiccant to ensure cavity dryness. The non-rigid barrier, which is typically metallized foil, functions as a barrier to gas permeation and moisture vapor transmission. The MVTR sealant, located on the exterior edge of the spacer system, also provides a barrier to moisture vapor transmission and gas permeability. The thermal conductance is governed by the MVTR and structural sealant conduction paths and to some extent the metal foil conduction.

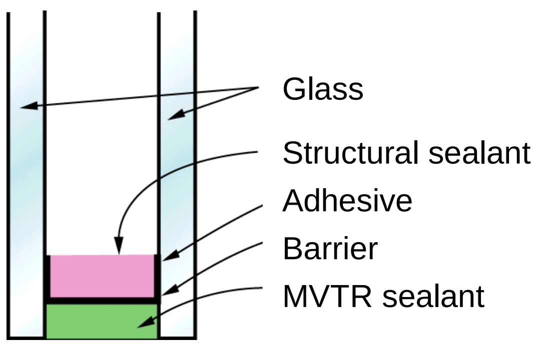

Figure 2-4. Non-rigid Barrier Spacer System

Figure 2-5 shows the thermoplastic spacer design class. This system contains only two primary elements: a structural sealant, and an MVTR sealant. In this configuration the structural sealant is located on the exterior edge, and provides the required compression and torsional rigidity. The MVTR sealant is located on the interior of the IG. The MVTR sealant has the desiccant embedded within it. This composite MVTR/desiccant configuration is thus used to provide MVT resistance, but also to capture the moisture which does pass through the sealant. The MVTR sealant also provides gas permeation resistance. Thermal conduction is minimized by eliminating the potential metal heat leakage path, and using the low conducting thermoplastic material.

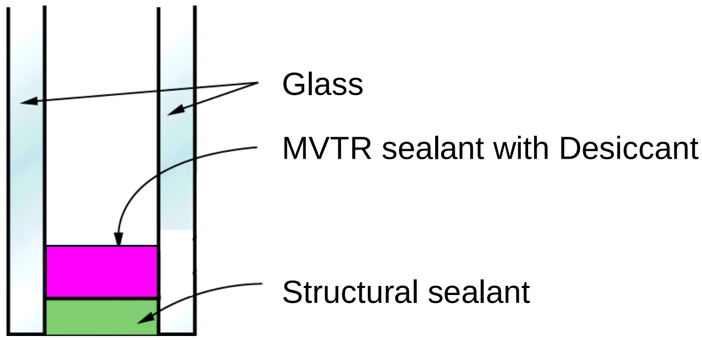

Figure 2-5. Thermoplastic Spacer System

The five design classes discussed in this section will be the basis of discussion for the remainder of this effort. Their structure and configuration will allow the construction of useful Failure Mode and Effects Analysis templates as well as meaningful Event Tree diagrams. Failure modes identified as typical for the design classes will be addressed to some depth. The mechanisms of failure for the design classes will be discussed qualitatively, and initial constructions of relevant analytical models will be supported. Field data, coupled with reliability analysis techniques, will be used to support reliability predictions for a specific manifestation of an identified design class. The design class definition allows these critical activities to commence.

As stated, there are significant material variations within each design class. The following sections will discuss materials of two components critical to all of the design classes: sealants and desiccants.

2.2 Insulating Glass Sealants

Overview

Sealants, used in insulated glass (IG) units, are polymeric materials with adhesive qualities used to join dissimilar components and provide an effective barrier against the passage of foreign materials, especially air, dust, water vapors and volatile organic substances, into the air space between two panes of IG unit.

Regardless of the type of sealant used in forming the insulating glass unit, the function of the sealant is twofold. First, the sealant must maintain the insulating glass unit in a hermetically sealed state, and, second, the sealant must have sufficient cohesive and adhesive strength to hold the glass panes and spacer element in a predetermined configuration. Failure of either one of these functions will cause failure of the IG unit.

A good sealant is characterized by:

- low water vapor transmission rate
- low content of volatile organic compounds (VOC)
- low gas loss rate for argon or krypton filled units
- high adhesive strength to glass and other IG components
- excellent durability under installation and exposure stresses
- low cost

Moisture in the space can condense on the glass and create visibility or aesthetic problems. The sealant must have a very low moisture vapor transmission rate (MVTR) to prevent moisture from entering the space between the panes of glass. If the sealant does not have a satisfactorily low MVTR rate, the desiccant capacity will be exceeded earlier, moisture will be visible in the interior, and the life of the IG will be reduced.

The sealant should be thermally stable with adhesive and cohesive properties that do not degrade due to environmental factors during its life. Environmental degradation factors generally include exposure to sunlight, moisture, and large changes in temperature. Furthermore, the sealant itself should not contaminate the IG interior. Should one or more constituents comprising the sealant volatilize into space, “chemical fogging” of the glass panes may result. Temperature variation will tend to cause contraction and expansion of the IG unit structure. Therefore, the sealant should have an elongation capability sufficient for the movement of the IG components. This may be in the range of at least 100%, and preferably at least 200%. The sealant should also resist degradation due to contact with conventional caulk and putties.

Construction of IG units has traditionally fallen into dual and single seal categories. Dual seal construction usually uses a PIB (polyisobutylene) compound as the primary seal with polysulfide, polyurethane, hot melt butyl, or silicone as the secondary seal. Single seal construction also uses polysulfide, polyurethane, and hot melt butyl rubber based sealants. Hot melt butyl sealants contain butyl rubber as a primary ingredient and may or may not contain polyisobutylene as a non-reactive component. In a hot melt butyl material, the butyl rubber is not fully cured and will soften with an increase in temperature. The hot melt butyls are compounded for ease of application, moderate adhesive strength, and good MVTR characteristics. The PIB (polyisobutylene) sealant used as a primary seal is compounded for minimum MVTR and has little inherent strength.

The PIB (polyisobutylene) primary seal acts as an excellent barrier to moisture and prevents the ingress of water vapor into the airspace as well as providing a soft cushion on the spacer shoulder. Some secondary seal materials may provide high resistance to moisture and also provide the structural element of the dual-seal system. The sealant strength holds the lites of glass together and maintains the integrity of the PIB (polyisobutylene) moisture barrier. The attributes of the two sealants in this system (PIB (polyisobutylene) – moisture barrier, second sealant – structural) each contribute in their own way to the results achieved with dual-seal construction.

Water vapor diffusion through sealants is proportional to the water pressure gradient across the sealant. The gradient is greatest in a new unit when the desiccant has adsorbed the initial water vapor and before additional moisture has penetrated the sealant. The gradient decreases with time as water vapor diffuses into the interpane space, the desiccant becomes saturated, and the moisture content of the air increases. The gradient is increased if the moisture content of air in the framing surrounding the IG unit (glazing cavity) increases. This might occur under the following conditions: during humid summer weather, penetration of precipitation, accumulation of condensate draining from the room-side surface of glazing in the winter, and condensation on the outer surfaces during air conditioning in summer. Water vapor diffusion through some materials may be adversely affected by relative humidity of the service environment.

Water vapor resistance of sealants depends on width and depth of the sealant, and consistency and continuity of application. Water accumulation in the framing and its prolonged contact with the IG unit perimeter seal is detrimental to IG unit perimeter sealants. A sealant MVTR is measured with differing water vapor pressure across the sealant. Liquid water in contact with the sealant gives a significantly different moisture transmission rate. Processing issues are a practical and significant factor in overall sealant performance. Processing issues can lead to internal flaws in the sealant as well as to flaws in the sealant's adhesion to the substrate. When such processing concerns lead to gas flow paths through the sealant, its effectiveness is compromised.

Sealant Characteristics

Various types of sealant are currently used in the manufacture of IG units, including both curing and non-curing systems. They are most commonly based on thermoset polymers such as liquid polysulphides, polyurethanes and silicones, which represent commonly used curing systems or consist of thermoplastic hot melt butyl rubber compounds. An understanding of these products and their inherent properties is a critical requirement in making the proper overall sealant choice for production of long durability IG units.

Curing, or crosslinking, sealants made from polysulfide, polyurethane, and polysiloxane provide adhesion of a chemical nature involving a chemical bond between glass, the spacer and the sealant, generally brought about through a chemical intermediate naming promoter. Adhesion of noncrosslinkable sealants, consisting of butyl based materials, is usually of a physical nature employing the sticky properties of butyl based polymer and any additives which contribute to tack. A sealant providing both chemical and physical adhesion of the glass and spacer element making up the insulating glass unit is particularly desirable.

The strength of the bonds between the substrates of the IG unit increases as the sealant gradually converts from a thermoplastic form to a cured elastomer that is not reflowable when heated to temperatures above the initial application temperatures.

Thiol terminated liquid polysulfide has low argon migration, good resistance to free radical oxidation, and good workability with polyurethane. Thiol terminated polysulfide polymers, because of their polar nature, are somewhat permeable to water vapor. For premium properties with regard to the exclusion of water vapor from the interior of IG unit, the application of a first sealant layer with a high impermeability to moisture vapor has been required.

Polyurethanes have a low MVTR, low water swell, good electrical resistance, good resistance to solvents and wood preservatives, and good adhesion to organic components of insulated glass windows.

Highly water impermeable PIB (polyisobutylene) sealants have inherent low physical strength and low elongation capability, so the use of a second higher strength sealant or mechanical support has been required to attain an adequate balance of premium moisture exclusion and structural strength. Hot melt butyls, as used for secondary sealants, are satisfactory at normal ambient temperatures, but subject to softening when exposed to heat. This characteristic is exaggerated at higher temperatures, which can occur in some locations and applications, especially those utilizing solar control glass. As a result, IG units made with hot melt butyl sealants do not have universal acceptance under all conditions.

Silicone sealants have high durability and long service life, superior adhesion to glass and various metal substrates, highly flexible joint movement, controlled viscosity and fast cure, low sag and high strength, superb resistance to temperature or weather extremes, UV radiation, and ozone degradation. Silicones are degradable by water and permeable to moisture vapor. Silicone IG sealants, in combination with a primary PIB (polyisobutylene) sealant, provide adequate environmental resistance and durability to IG units. The higher temperature and strength characteristics of silicone sealants have resulted in silicone sealants being the only code acceptable material for use in curtain wall IG construction.

Sealant Chemistry

Polysulfide compounds are viscous liquids having molecular weight of 1,000 - 8000. The liquid polysulfides are the linear compounds. Linear polysulfides are prepared by the condensation, in aqueous suspension, of sodium polysulfide with bis-(2-chloroethyl)formal:

$$Cl\text{-}CH_2CH_2\text{-}O\text{-}CH_2\text{-}O\text{-}CH_2CH_2\text{-}Cl + Na_2S_x \text{ -------}\rightarrow$$

$$\text{-------}\rightarrow \quad H\text{-}(SCH_2CH_2\text{-}O\text{-}CH_2\text{-}O\text{-}CH_2CH_2\text{-}S)_n\text{-}H$$

The addition to a reaction mixture of the small amount of 1,2,3-trichloropropane ($Cl\text{-}CH_2CHCl\text{-}CH_2\text{-}Cl$) along with the bis-(2-cloroethylformal) permits the production of a branched polysulfide:

$$H\text{-}(S\text{-}CH_2CH_2\text{-}O\text{-}CH_2\text{-}O\text{-}CH_2CH_2\text{-}S)$$

Addition of 1,2,3-trichloropropane ($Cl-CH_2CHCl-CH_2-Cl$) to the reaction mixture also leads to incorporation of $-SCH_2-CH(SH)-CH_2S-$ groups into polymer chains and polymer branching. The interspersal of HS-groups in the chain of polysulfide provides for crosslinking. The general structure of polysulfide is described by the formula:

$$H-(S-C_2H_4-O-CH_2-O-C_2H_4-S)_x-(S-CH_2-CH(SH)-CH_2-S)_y-H$$

Wherein x = 5 – 50, y = 0 –1 and x/y = 0.002 – 0.02 always > 0.

Curing agents are: metal oxides like MnO_2, PbO_2, ZnO, $Na_4Mn_{14}O_{27}x9H_2O$ (sodium birnessit) and amine or alkaline accelerators.

Lead peroxide PbO_2 catalyzing condensation reaction between, discussed above, low molecular weight polysulfide prepolymers with said HS-groups is chain lengthening and crosslinking via -S-S- bonds formation:

O=Pb=O

SH SH SH SH

HS ~~|~~SH + HS~~|~~SH + HS~~|~~SH → HS~|~S-S~|~~SS~|~SH

O=Pb=O SH S

\+ O=Pb=O (catalyst) | SH

HS~~|~~~SH S~~|~~~SH

SH

\+ 3PbO + $3H_2O$

Polyurethanes are defined as polymers which contain urethane groups(-NH-CO-O-) in the main polymer chain. However, it is to be noted that in technologically useful polymers of this type such as ester, ether, amide and urea groups are generally contained in the polymer chain in appreciable number. Several kinds of polyurethanes are of commercial significance and are conveniently classified into the following major types-flexible foams; rigid foams; integral foams; elastomers; surface coatings; synthetic leather and adhesives.

The urethane group results from the interaction of an isocyanate and hydroxyl compound:

$$R\text{-}NCO \quad + \quad HO\text{-}R' \quad \longrightarrow \quad R\text{-}NH\text{-}CO\text{-}O\text{-}R'$$

It will be apparent that this reaction leads to polyurethanes when multifunctional reactants are used. When a diisocyanate and a diol react together a linear polyurethane is obtained whilst a diisocyanate and a polyol lead to a cross-linked polymer. Cross-linked polyurethane could also be derived from a compound containing three or more isocyanate groups and a diol but this approach is of limited commercial importance. Thus diisocyanates and diols and polyols are the principal raw materials used in the manufacture of polyurethanes. The more important of these reactants are described here.

Several reactions are known by which isocyanates are formed. However, there is only one method of preparation of commercial importance, namely phosgenation of primary amines:

$$R\text{-}NH_2 \quad + \quad COCl_2 \quad \longrightarrow \quad R\text{-}N{=}C{=}O \quad + \quad 2HCl$$

Several kinds of diisocyanate are described by the following: toluene diisocyanate; diphenylmethane diisocyanate; naphthylene 1,5-diisocyanate; hexamethylene diisocyanate; isophorone diisocyanate.

The earliest polyurethanes were based on aliphatic diols (glycols) and, of the various glycols investigated, 1,4-butanediol was generally preferred for commercial operations. Since this time, however, production of polyurethanes has mainly involved polymeric hydroxyl compounds. The use of these materials permits the manufacture of a much wider range of products at relatively low cost.

The polymeric hydroxyl compounds which have received most attention are polyesters and polyethers. Polyethers are now used in about 90% of commercial polyurethanes whilst polyesters are used in most of the remainder.

Several kinds of diols and polyols are described by the following: polyethers; polyesters; polycarbonates; polycaprolacton; ethylene glycols; 1,4-butane diols; 1,6-hexnae diols; diethylene glycol.

Isocyanates are very reactive materials and undergo a great many reactions. Below, those reactions which have technological significance are described. The common addition reactions with compounds containing active hydrogen and self-addition. The more important reactions involving active hydrogen compounds are shown below.

Reaction with alcohols:

R-NCO + R'-OH ----> R-NH-CO-O-R' (a urethane)

Reaction with amines:

R-NCO + R'-NH_2 ----> R-NH-CO-NH-R' (a urea)

Reaction with carboxylic acid:

R-NCO + R'-COOH ----> [R-NH-CO-O-CO-R'] (anhydride) ---->

--->R-NH-CO-R' (amide)

Reaction with water:

$R\text{-}NCO + H_2O$ ----> [R-NH-COOH] (a carbamic acid) ---->

--→R-NH_2 (amine)

Reaction with urethanes:

R-NCO + R'-NH-CO-O-R" ----> R-NH-CO-N(R')-CO-O-R"

(allophanate)

Reaction with urea:

R-NCO + R'-NH-CO-NH-R" ----> R-NH-CO-N(R')-CO-NH-R"

(biuret)

Reaction with amides:

R-NCO + R'-NH-CO-R" ----> R-NH-CO-N(R')-CO-R" (acrylurea)

The secondary IG sealants are often the polyurethane moisture curing products. The sealants of first generation are made from isocyanate prepolymers, the reaction product of a polyol with excess isocyanate. The prepolymers are high in viscosity, which gives excellent initial bond strengths; however they require an application temperature of 90-100°. The sealant is coated onto the first PIB sealant, and atmospheric moisture reacts with the excess isocyanate groups to crosslink the urethane after the secondary film has been mated to the primary film.

The curing mechanism is:

R-NCO + H20 -> R-NH2 + C02

R-NH2 + R'-NCO -> R-NHCOHN-R'

The problems encountered with these first generation sealants are bubbles in the sealant layer and inconsistency of the cure rate. As mentioned before bubbles are produced by the by-product carbon dioxide of the curing reaction and can be trapped when high barrier films are first created. The amount of atmospheric moisture that comes in contact with the sealant as it is coated can lead to an inconsistency in the cure rate. Moisture is often added to the primary film by means of a spray boom just prior to nipping the secondary film. This addition will increase the rate of cure.

The next major advancement in urethane sealants was the development of two-part polyurethane sealants. These products are comprised of polyurethane prepolymer and a polyol, both low in viscosity. The components are mixed together at room temperature and pumped onto the coating station of the laminator through an in-line static mixer. The meter-mix, in combination with the static mixer, ensures that the proper ratio of adhesive components is present and completely mixed, resulting in a consistent cure rate.

The second generation curing mechanism is:

$$R\text{-}NCO + HO\text{-}R' \rightarrow R\text{-}NHCOO\text{-}R'$$

The problems encountered with these second generation sealants include low initial bond strengths and the presence of high residual isocyanate monomer. The low initial bonds are a result of the low viscosity of both adhesive components, which means tighter controls are needed before the sealant has a chance to properly cure. Cure time is 12-48 hr.

The high residual isocyanate monomer causes a phenomenon known as anti-seal, which occurs when the isocyanate monomer migrates through a soft sealant film such as polyethylene and reacts with atmospheric moisture. This reaction creates a very hard and thermally stable polyurethane layer that renders the second seal unsealable. In addition to the anti-seal problems, there are possible health risks due to worker exposure from the high residual monomer. Finally, the presence of isocyanate monomer requires EPA documentation and reporting, which can be a time-consuming burden for such a process.

To address the problems associated with using first or second generation solventless sealants, third generation two-part polyurethane sealant systems that have a consistent cure rate, low residual monomer and increased initial bond strengths have been developed. Typical third generation sealants are based on moderate viscosity polyurethane polymers that require a 50-70° C application temperature. The increased viscosity of third generation products versus second is a result of higher-molecular-weight polymers.

The third generation adhesives are made from a process that removes nearly all of the excess isocyanate monomer from the prepolymer component, consistently resulting in a blended adhesive system with less than 0.08% free isocyanate. The low residual isocyanate monomer eliminates the anti-seal issue, health concerns from worker exposure to isocyanate monomers and the regulatory documentation associated with isocyanates.

The third generation curing mechanism is:

R-NCO + HO-R' -> R-NHCOO-R'

The sealant has excellent machining properties. However, the majority of IG producers in the United States still are applying a secondary generation sealant system.

Polyurethane curing agents include: tetramethylbutandiamine, 1,4-diazobicyclo [2,2,2]octane, stannousoctanoate, and dibutyltindilaurate

With the above described polyaddition urethane formation no reactive by-products such as water, alcohol, sodium chloride and other are created. Polyurethane with very good hydrolytic stability is obtained by reaction of liquid, hydroxyl-terminated homopolymers of butadiene with diphenylmethane diisocyanate (MDI).

$OH-\{(CH_2-CH=CH-CH_2)_m-[CH_2-CH(HC=CH_2)]_n-(CH_2-CH=CH-CH_2)_p\}-OH$ + $O=C=N-C_6H_5-CH_2-C_6H_5-N=C=O$ → polyurethane

Such polyurethane film of 2 mm thickness exhibits a Moisture Vapor Transmission Rate (MVTR) of 0.3 gm/100 in^2/24 hr (Elf Atochem North America Inc., Philadelphia). Excellent water-absorption rate is due to the fact that the hydrophobic backbone of the polybutadiene surpasses that of any other type of polyurethane.

Liquid polysiloxanes are acetoxy, enoxy, oxime, alkoxy or amine terminated polysiloxane with molecular weights from 15,000 to 150,000. These compounds are obtained by reaction of silanol functional polymers with an excess of multi-functional polysiloxane:

$$HO-Si(CH_3)_2-O-[Si(CH_3)_2-O]_n-Si(CH_3)_2-OH + 2CH_3-Si(OR)_3 \dashrightarrow$$

$$CH_3(RO)_2Si-O-Si(CH_3)_2-O-[Si(CH_3)_2-O]_n-Si(CH_3)_2-O-Si(OR)_2CH_3 + ROH$$

R = CH_3, C_2H_5, CH_3CO, $C_2H_5(CH_3)C=N$

Curing agents: dibutyltinlaurate, stannousoctanoate, and titanates.

Polyisobutylene is a hydrocarbon polymer described by the formula:

$$n\ (CH_3)_2C=CH_2 \dashrightarrow (CH_3)_2C=CH_2-[C\ (CH_3)_2-CH_2]_n-C\ (CH_3)_3$$

Hot melt butyls have shown promise due to low MVTR and some structural capability. Butyl rubber is a copolymer of isobutylene and isoprene:

$$CH_2{=}C(CH_3)_2 + CH_2{=}C(CH_3){-}CH{=}CH_2 \rightarrow -[CH_2{-}C(CH_3)_2]_n{-}CH_2{-}C(CH_3){=}CH{-}CH_2{-}$$

Isobutylene and isoprene are in a ratio of approximately 50/1. Isoprene is incorporated in relatively small proportions to introduce sufficient unsaturation needed for curing.

2.3 Insulating Glass Desiccants

Background

Insulating glass (IG) units are used in modern construction in place of single panes of glass when reduced energy loss is needed. Insulated glass units consists of two panes of glass separated by an air (or gas) filled space which provides the insulation in the unit. The space between the panes is sealed to prevent dust, dirt, and moisture from settling on the interior glass surfaces and obscuring vision through the unit. When the first IG assemblies were made and sealed, ambient moisture was left between the glass panes. At lower temperatures, this moisture would condense on the glass. Condensation of moisture on glass is not normally a problem where the glass can be washed on a regular basis. Within the sealed unit, washing of the glass was not possible, and one of the long term effects of condensation is leaching of constituents from within the glass structure and etching of the glass surface. The deposit of moisture condensation and/or leachate on the glass surface can obscure vision through the unit.

One of the earliest ways to remove this moisture was to seal a desiccant (such as silica gel) within the unit. Testing and field experience showed that maintaining a dew point below -20º F was desirable to prevent condensation in colder climates. The requirement of maintaining a -20º F dew point was formalized in ASTM E-774 standard for CB and CBA ratings. When testing IG units for certification, an end of test dew point greater than -20º F is considered a failure. Vapor pressure and dewpoint tables (Ref. Smithsonian Meteorological Tables, 1966) shows that at -20F, saturated air contains water at a vapor pressure of 0.008195 psia over water (0.006185 psi over ice). When an IG is tested for dewpoint per ASTM E-546 at room ambient conditions of 75 F, a -20º F dew point corresponds to a relative humidity of 1.90 % within the unit.

At this low relative humidity, silica gel and many other desiccants have a very low moisture capacity and are not very effective desiccants (see Figure 2-1).

A further important attribute for keeping the interior glass surface of an IG unit clear is the ability of a desiccant material to capture and hold heavier contaminants, such as organic or chemical vapors from materials used in manufacturing the unit, from condensing on the interior surfaces and causing fogging of the unit. Molecular sieve desiccants were found to fulfill both of these requirements. Desiccant properties are described later. Molecular sieve desiccants are manufactured synthetic zeolites.

Overview

After an IG unit is sealed, moisture vapor continues to enter through the sealant throughout the entire life of the window, due to the differential vapor pressure between ambient air and the sealed dry atmosphere inside the IG. The rate of moisture vapor transmission into an IG unit depends on sealant characteristics, assembly methods, and outside pressure, temperatures, and humidity. No organic sealant has an infinite resistance to water vapor diffusion, therefore, over time water vapor will diffuse into the inter-pane space. The concentration of moisture and volatile organic compounds (VOC) inside the window cavity is normally controlled by use of a desiccant [3-8]. Desiccant materials have a very high affinity for water vapor. Their moisture absorption capability is a function of the relative humidity of the surrounding air. The IG desiccation process involves separation and immobilization of moisture vapor from the atmosphere inside the IG unit.

Two major categories of desiccants are absorbents and adsorbents. Absorbents go through a chemical/physical change as they attract and retain water vapor. Adsorbent materials hold water molecules in pores at their surface; no chemical/physical change results. The definition of adsorption is the adhesion in an extremely thin layer of molecules (as of gases, solutes or liquids) to the surface of a solid or liquid with which they are in contact. Chemically inert solid adsorbents are excellent desiccants for drying of IG units.

There are three major adsorbents used as desiccants today: silica gel, activated alumina and molecular sieves. Adsorption of water, with these solid adsorbents, is a surface phenomenon involving the removal of water molecules into the adsorbent's pore structure where it is held mainly by van der Waals and electrostatic forces. Water sorption is an equilibrium process with water adsorption/desorption strongly dependent on thermal and pressure conditions. A large specific surface area is preferable for providing large adsorption capacity. A microporous adsorbent having a large internal surface area in a limited volume is preferable for many practical applications. The plot of equilibrium adsorption capacity is called an adsorption isotherm. The isotherms for different possible adsorbents can be compared to determine the optimum adsorbent for a particular application. The characteristic curves for adsorption of water on activated alumina, molecular sieves, and silica gel are shown below in Figure 2-1 as per cent by weight absorbed water versus relative humidity of the air in contact with adsorbents.

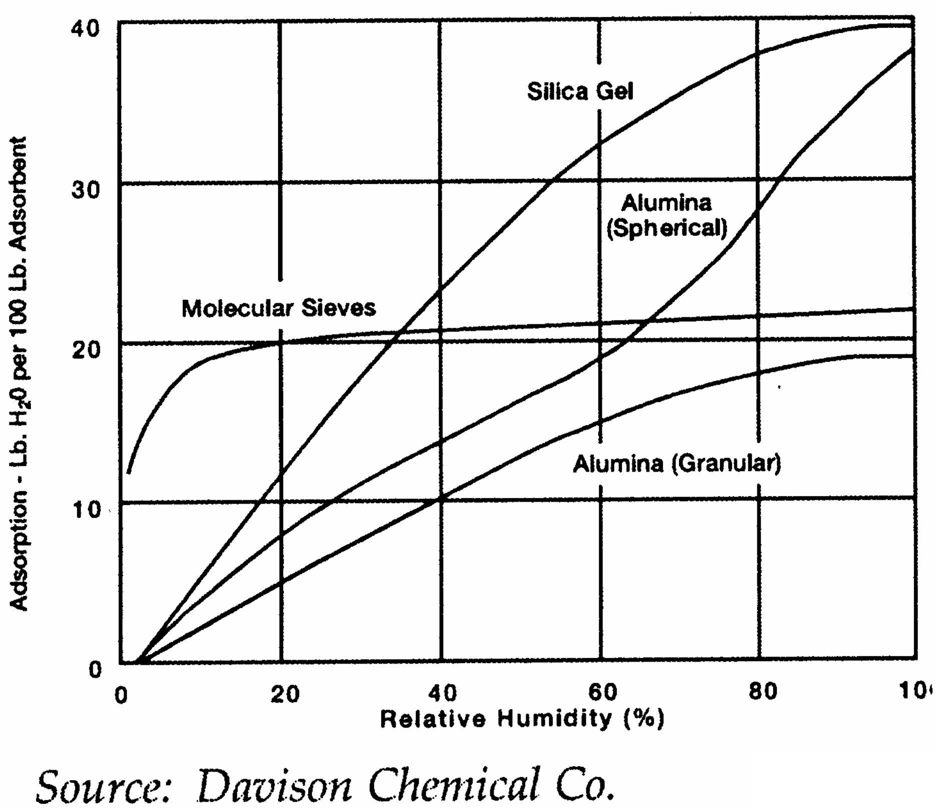

Figure 2-1. Desiccant Effectiveness

The amount of water adsorbed on silica gel rises almost linearly with increasing relative humidity until RH reaches about 60%. It then plateaus out at about 40% adsorbed water as relative humidity approaches 100%. Analogous curve for water adsorption on granulated alumina rises slowly and plateaus out at about 17% adsorbed water at 100% RH. The curve for spherical activated alumina is more complicated. It linearly rises with a speed that is higher than for granular alumina until RH reaches about 10%. After that adsorption processes linearly slow down until about 60% RH and then linearly rise rapidly until relative humidity reaches 100%. The curve for molecular sieves, by contrast to other adsorbents, rises rapidly to plateau at about 20% adsorbed water at 20% RH.

Analysis of characteristic curves for adsorption of water on these the commonly used, commercially available, inert, solid adsorbents helps to explain why the molecular sieves are an excellent desiccant choice for manufacturing of IG units which require very low internal moisture content. Since "good" IG units are defined as having an internal dew point below -20 F at 75 F ambient temperature (internal humidity of 1.6% RH) molecular sieves are the best choice desiccant with a significant moisture capacity under these conditions.

Silica gel (SiO_2 xH_2O) is a solid, porous form of polysilicic acid made by a process in which a silica sol is aggregated to form a solid gel structure. Silica gel has an amorphous micro-porous structure with a distribution of pore opening sizes of roughly 3 – 70 angstroms and exhibits 500 m^2/g specific surface area. Silica gel is regarded as the highest humid adsorbent in the desiccant community. Its interconnected pores form a vast surface condensation area, allowing silica gel to adsorb moisture up to 40% of its weight (per Figure 2-1) at 100% humidity environment. Silica gel usually is used when dryness need be no lower than -60^0 F dew point. This desiccant does not have capacity to remove water to very low dew point levels. Silica gel is efficient at temperatures below 77^0F (25^0C) but loses its adsorption water capacity as temperature begins to rise.

Activated alumina (Al_2O_3) is produced from aluminum hydroxide by controlled thermal treatment to eliminate most of the water in the crystal lattice. Spherical activated alumina has highly microporous structure with distribution of pore opening size 5 – 60 Å (angstroms) and exhibits a high specific surface area of 350 m^2/g. At 100% RH (relative humidity) spherical activated alumina has a water capacity comparable with silica gel but rapidly loses its adsorption capacity as humidity begins to decrease. Granulated activated alumina has a water pickup rate of 17% at 100% RH, which is much lower than silica gel. It has a bit lower adsorption capacity than spherical activated alumina when relative humidity is not more than 60%. Activated alumina has the ability to dry when dryness need be about - 90^0 F dew point. A dew point of – 90^0 F contains water in air of only 6.5 parts per million. Application of activated alumina desiccant is very efficient at high relative humidity and at low temperature. Comparison of the sorption properties shows that activated alumina performs very similar to silica gel, providing somewhat lower moisture capacity at low temperatures, but slightly improved capacity at higher temperatures.

Molecular sieves have the lowest ultimate water capacity in the desiccant community. They adsorb moisture to only 25% of their weight at 100% RH. Molecular sieves are by far the most effective water adsorbents due to their uniform network of crystalline pores and empty adsorption cavities, which give them an internal specific adsorption surface area of 700 to 800 m^2/g. Molecular sieves having uniform angstrom pore sizes of 3A, 4A, 5A and 10A(13X) are commercially available. Molecular sieves do not give up moisture as readily as silica gel and activated alumina which have wide pore size distributions. For purposes of comparison, the heat of adsorption for water on molecular sieve is about 1800 BTU/lb. of water absorbed, as compared to 1300 BTU/lb. of water absorbed on silica gel. Molecular sieves have the ability to dry to a -120^0F dew point and thus they are used as the basic desiccant in the most demanding and unique drying application of manufacturing of IG units.

Molecular sieve properties as IG desiccants differ from silica gel and activated alumina in a number of ways:

1. Molecular sieves adsorb water vapor more rapidly than silica gel and activated alumina.

2. Molecular sieves reduce water vapor to lower levels than silica gel and activated alumina, making their use essential when a very dry atmosphere is required.

3. Molecular sieves perform more effectively as moisture absorbers at higher temperatures (greater than 77^0F) than silica gel and activated alumina.

4. Molecular sieves have the highest moisture adsorbant capacity at the -20º F dew point required for IG units.

The choice of edge sealant for the IG units determines the volume of desiccants to be used for preventing condensation and fogging [5, 6]. However, desiccants have a finite capacity for absorption of water vapor. As this capacity is used, the internal dew point increases. At some point, the water vapor content will be sufficiently high for condensation of water vapor to occur within the internal IG space. When this occurs such that vision is obstructed, the IG unit is removed, discarded, and a new unit installed.

As mentioned above, molecular sieve desiccants are adsorbents having the highest adsorption capacity for moisture, in the conditions in an IG unit, of all commercially available adsorbents and, if required, they also can remove solvent vapor [14].

Molecular sieves are synthetic hydrated zeolites or aluminosilicates having a network of pores whose diameters are strictly defined as 3, 4, 5, or 10 angstroms [10-14]. It is these diameters measured in angstroms that classify molecular sieves – 3A, 4A, 5A, and 10A (also known as 13X) grades [15].

The combination of a uniform porous structure with a high adsorption capacity enables the selective adsorption of molecules [16]. The term 'molecular sieve' derives from the ability to sieve molecules. Molecular sieves differ from other adsorbents, such as silica gel or activated alumina, which have very wide pore distribution. Adsorption occurs only of molecules with smaller diameters than these cavity openings. Larger molecules will be excluded from adsorption. Preferentially adsorbed are molecules of greater polarity. This makes molecular sieves ideal for adsorption of water from air and liquids, as water molecules are both polar and very small. Molecular sieves will adsorb water molecules and other contaminants from liquids and gases down to very low levels - often to just 1 part per million.

A variety of conditions and effects are involved in the optimum selection of a molecular sieve desiccant for an IG unit. For moisture adsorption only, 3A grade is most effective, since this pore size will admit water molecules and reject all other commonly found materials. Grade 13X will adsorb organic molecules as well as argon, nitrogen, and water. When grade 13X has adsorbed an organic molecule and then is presented with a water molecule, the organic molecule is ejected and replaced by the water molecule. If 13X were completely free of adsorbed gases when placed into an IG unit, it would adsorb some of the nitrogen or argon present and cause loss of internal pressure in the unit. Grades other than 3A and 13X are not commonly used in current IG production. Balancing the needs for water and organic adsorption with the need to prevent excessive deflection of the glass has resulted in the use of a blend of about 90% 3A with about 10% of 13X material. Some blends may include a small amount of silica gel for organic adsorption in addition to the molecular sieve material.

The term zeolite was originally coined in the 18th century by the Swedish mineralogist Cronstedt [14]. He observed that upon rapidly heating natural aluminosilicates, the stones began to dance about as the water evaporated. Using the Greek word meaning "stone that boils," he called this material zeolite. A commonly used description of a zeolite is a crystalline aluminosilicate with a cage structure. Technically, we speak of a zeolite as a crystalline hydrated aluminosilicate whose framework structure encloses cavities (or pores) occupied by cations and water molecules, both of which have considerable freedom of movement, permitting ion exchange and reversible dehydration. This class of materials was then defined as "molecular sieves."

More than 150 zeolite types have been synthesized [17] and 40 naturally occurring zeolites are known [18,19]. Zeolites occur as hydrates, and all members of the family contain at least one silicon atom per aluminum atom. The formula of one of the better known sodium zeolite A is as follows:

$$Na_2O \cdot Al_2O_3 \cdot 2SiO_2 \cdot 4.5\ H_2O$$

Zeolites form in nature as a result of the chemical reaction between volcanic glass and saline water [18]. Temperatures favoring the natural reaction range from 27°C to 55°C and the pH values are typically between 9 and 10. Nature requires 50 to 50,000 years to complete the reaction. Naturally occurring zeolites are rarely phase-pure and are contaminated to varying degrees by other minerals [e.g. Fe^{++}, SO_4^-, quartz, other zeolites, and amorphous glass]. For this reason, naturally occurring zeolites are excluded from many important commercial applications where uniform pore size and purity are essential.

Synthetic zeolites are made by reacting sodium aluminate $NaAl(OH)_4$ with sodium silicate $NaSiO_4$ according to the following reaction [17,19]:

$$NaAl(OH)_4 + NaSiO_4 \rightarrow Na_2O.xAl_2O_3.ySiO_2 + nH_2O$$

Sodium aluminate is produced by reaction of hydrated alumina $Al(OH)_3$ with caustic soda NaOH.

Synthetic zeolites are precipitated from solution in the form of fine crystals with a size of about 5 µm. Larger naturally-formed agglomerates of the alumina silicate crystals readily break up into smaller particles when handled. These small size crystal particles are difficult to contain and thus not too satisfactory for use as practical adsorbents. Industrial products are obtained in the form of fine powders whether they originate from natural deposits, or industrial synthesis operations.

For their practical application as adsorbents, the crystals are processed into larger particles of various shape and sizes by pelletizing or extrusion or by agglomeration [13]. In a processing facility, zeolite powder usually is mixed with conventional binders (a clay mineral such as attapulgite, bentonite or kaolin) and agglomerated. Clay aluminosilicate minerals are naturally occurring materials having some adsorbent capacity.

Some adsorbent spherical particles with an upper size range of about 300µm are produced by spray-drying solution agglomerated zeolites. Large spherical molecular sieves with particle size 0.5 – 2.0 mm, used in IG manufacturing, are produced by agglomeration in a fluidized bed.

One of the last steps in preparing molecular sieves for use as desiccants is the final drying of the material to remove all moisture from the precipitation stage through the pelletizing or agglomeration stage. Drying is typically done at an elevated temperature and/or reduced pressure. After final drying the material is packed in sealed containers until use.

Agglomeration, drying and calcining processes permit obtaining molecular sieves of 3A, 4A, 5A and 10A/13X types that are sub-classified by their bead sizes, typically 1.0 – 2.0 mm, 1.6 - 2.5 mm, 2.0 – 3.0 mm, and 2.5 – 5.0 mm. Agglomeration with aluminosilicate binders leads to desiccants with a hard (Crushing strength 6 – 14 N), clear and smooth surface, having a density of ~ 800 kg/m^3 and a high absorbing capacity for water of ~ 205 mg/g, at 50% RH.

Synthetic zeolites hold some key advantages over their natural analogs [17]. The synthetic zeolites can, of course, be manufactured in a more uniform, phase-pure state. It is also possible to manufacture desirable zeolite structures not appearing in nature. Mentioned above, Zeolite A is a well-known example.

All commercially useful zeolites owe their value to one or more of three properties: adsorption, ion exchange, and catalysis. From these properties adsorption is most valuable for IG manufacturing.

Zeolite Adsorption

The most fundamental consideration regarding the adsorption [10,17] of chemical species by zeolites is molecular sieving. Species with a kinetic diameter making them too large to pass through a zeolite pore are effectively "sieved." This "sieve" effect can be utilized to produce sharp separations of molecules by size and shape.

The particular affinity a species has for an internal zeolite cavity depends on electronic considerations. The strong electrostatic field within a zeolite cavity results in very strong interaction with polar molecules such as water. Non-polar molecules are also strongly adsorbed due to the polarizing power of these electric fields. Thus, excellent separations can be achieved by zeolites even when no steric hindrance occurs.

Adsorption based on molecular sieving, electrostatic fields, and polarization are always reversible in theory and usually reversible in practice [13]. This allows the zeolite to be reused many times, cycling between adsorption and desorption. This accounts for the considerable economic value of zeolite in adsorptive applications.

Because cations are free to migrate in and out of zeolite structures, zeolites are often used to exchange their cations for those of surrounding fluids. Sodium zeolite A is among the world's most efficient removers of water hardness ions. This is its principal function as a detergent builder.

Industrial molecular sieve adsorbents are crystalline, hydrated alkali-aluminum-silicates of the general formula [14]:

$$M_{2/n}O.Al_2O_3.xSiO_2.yH_2O$$

Where M = cation of element IA and IIA groups, n is cation valence, x = 2 or greater, y is the number of water molecules contained in the channels or interconnected voids within the adsorbent. The M cations are mobile and capable of undergoing ion exchange. This exchange process is utilized in preparing specific pore size materials from the basic crystallization product such as the preparation of 3A material by exchanging potassium in place of sodium.

Zeolite's unique structure allows the water of crystallization to be removed, leaving a porous crystalline structure. These pores or "cages" want to re-adsorb water or other molecules. Aided by strong ionic forces caused by the presence of cations such as sodium, calcium and potassium, the molecular sieve will adsorb a considerable amount of water or other fluids. If the fluid to be adsorbed is a polar compound, it can be adsorbed with high loading even at very low concentrations of the fluid. This strong adsorptive force allows molecular sieves to remove many gas or liquid impurities to very low levels (PPM or less).

Another feature of molecular sieve adsorbents is its ability to separate gases or liquids by molecular size. The pore or "cage" openings are of the same size as many molecules. In the case of a hydrocarbon paraffin, the normal, straight chain molecules can fit into the pores and be adsorbed while the branched chain molecules cannot enter the pores and pass by the molecular sieve adsorbents unadsorbed.

Molecular sieves usually adsorb moisture in the air space between two panes of glass and play a minor role in deflection and stress of most IG units [5]. One should select a type of molecular sieve that minimizes air adsorption, and thus deflection, while maximizes water vapor adsorption. Therefore, low air adsorbing molecular sieves will provide maximum protection under severe climatic conditions and should be used when manufacturing insulating dual pane sealant units using hot melt sealant. The use of molecular sieves is thus an important cost factor in the production of IG units.

As mentioned above there are many types of crystals and cationic forms of molecular sieves. Some of the more common types of molecular sieves include the following: 3A, 4A, 5A, 13X, Y, Pentasils, and Mordenite [15].

The Type 3A molecular sieves exclude most molecules except water. It used for natural gas dehydration, cracked gas dehydration, olefin drying, methanol and ethanol drying, removing water from cleaning fluids in ultrasonic baths, etc. Molecular sieves Type 3A is prepared by ion exchanging potassium onto a Type 4A in place of sodium.

The sodium form of zeolite crystal Type 4A is an inexpensive adsorbent and is usually used as a general dryer of liquids, natural gases, and also is an excellent adsorber of carbon dioxide.

Molecular sieve Type 5A is a calcium exchanged form of the Type A crystal. The strong ionic forces of the divalent calcium ion makes Type 5A molecular sieves an excellent absorbent for removing carbon dioxide, hydrogen sulfide and other weakly polar molecules. This adsorbent is also used for separating normal straight chain hydrocarbons from branched hydrocarbons.

Type 10A/13X molecular sieves are the sodium form of the Type X crystal having a much larger pore opening than the Type A crystal. This crystal also has the highest theoretical capacity of the common adsorbents and very good mass transfer rates. It can remove impurities too large to fit into a Type A crystal and is commonly used to separate nitrogen from oxygen. Due to high water and carbon dioxide adsorption capacity these molsieves are used in air pre-purification. They are used for removing the sulfurous compounds and decomposition products following the quenching of arcing in electrical articles.

Type Y crystal is similar to the X crystal except it has a higher silica to alumina ratio. It is better than 13X in some applications. In the high silica/alumina ratios it can adsorb hydrophobic molecules in the presence of water and has mild acid resistance.

Pentasils are high silica/alumina ratio crystals that can remove organics from gas and liquid streams containing water.

Mordenite is a highly acid resistant adsorbent.

Desiccant Applicability in Common Practice

As mentioned above desiccant's primary function is to adsorb any moisture that has been trapped between the glasses during the production of an insulating glass (IG) unit [5,6]. Also, desiccants maintain low moisture levels (low dewpoint levels) over the life of the IG unit by adsorbing any moisture that penetrates the unit during its life span. Historically, silica gel, 3A molecular sieve, 4A molecular sieve, 13X molecular sieve, and their blends have been used for desiccation of IG units.

Type 13X desiccant can also adsorb many organic vapors that may be present in the IG unit.
The attraction for water on molecular sieves of 3A, 4A and 13X types is similar. When 3A desiccant is present with 13 X, moisture is preferentially adsorbed on the 3A material.

Molecular sieves of 3A and 4A types have no capacity for hydrocarbon adsorption because their pore sizes are too small. Molecular sieve of 13X type has a good pore size for the hydrocarbon adsorption. Blends of 90% 3A with 10% 13X are used as water/hydrocarbon adsorbents in IG units.

It has long been recognized that the hydrocarbon capacity of type 13X molecular sieve is dramatically reduced when water is present. When an IG unit contains both 3A and 13X desiccant, moisture is first adsorbed by the 3A material. When the 3A material reaches its capacity, the excess moisture begins to be adsorbed by the 13X material and displaces any organic materials that have been previously adsorbed. Toward the end of life, an IG that had no visible fogging may begin to show fogging as the organic vapors are released from the 13X desiccant and begin to condense of the interior of the glass.

Blends of 3A molecular sieve and silica gel operate in a similar manor with the silica gel adsorbing organic materials.

As mentioned above, molecular sieves are available in spherical beads, cylindrical pellets, powder and paste form, with beads as the predominant form used in hollow spacer type construction. The solid beads are commonly held in a generally rectangular aluminum or stainless steel tube spacer of IG units [23,24]. The spacer is either perforated or not completely sealed so that inter-pane air may have contact with the adsorbent beads. While this basic IG technology has been used for many years, the conventional clay-bound adsorbent beads may present handling problems when clay-bound adsorbent beads contain fine dust. This dust is caused in part by the fact that clays are powdery materials by nature and also from abrasion of the beads during handling. Organic polymer-bonded adsorbent beads are usable as a direct replacement for conventional clay-bound beads in IG units [25]. Polymer-bound beads provide good adsorption and superior crush strength compared to clay-bound adsorbent beads.

The use of desiccated resins which are adhered directly to the special designed spacers or by use of special spacer constructions whereby the spacer is formed in part by a desiccated resin show good results.

Desiccated urethane and silicone polymers, and special desiccated polyisobutylene mastics are used as moisture preventive materials in the U-channel Intercept IG spacer introduced by PPG

Industries, Inc PPG's Intercept. ® [26]. Desiccated silicone foam is used as a flexible IG spacer commercialized under the name of SuperSpacer ® (Edgetech) [27].

Spacers made from flat metal strip bent in a continuous zigzag profile, which is embedded within an elongated ribbon of desiccated deformable butyl rubber is marketed commercially under the name of Swiggle Seal. ®. (Tremco Inc.) [28].

The introduction of desiccated polymers as moisture adsorbents and materials for spacer production of IG units has reduced perimeter heat loss. These new "warm edge" products also improve the efficiency and the speed of manufacturing the IG units [5,6].

Although these marked improvements of insulated glass production were done recently, the proper desiccant selection and usage remain an important topic of better performance and long life of argon-filled IG units.

The drive toward lower U-values has created rapid growth in the production of argon-filled IG units. Desiccant choice and usage can have a substantial impact on the argon concentration and the life of argon-filled IG units. Historically, silica gel, 3A, 4A, 13X molecular sieves, and their blends have been used for desiccation of IG units. All of the aforementioned molecular sieves strongly adsorb water and can be used for protecting the IG unit against moisture fogging. Of these desiccants, 4A molecular sieves is the least expensive to manufacture; silica gel is the most expensive. Types of 3A and 4A molecular sieves have no capacity for hydrocarbons that are a common impurity in IG units. This leaves 13X and silica gel to be considered for hydrocarbon removal. The hydrocarbon capacity of 13X type molecular sieves is dramatically reduced if water is present. Types of 13X and 4A molecular sieves adsorb and desorb nitrogen and argon as the temperature and pressure change inside the IG unit. The IG unit pressure changes from the adsorption/desorption of argon or nitrogen and cause glass deflections. These deflections distort reflected images, stress or destroy the seal, harm the U-value and reduce the life of argon-filled IG units. A blend of 3A molecular sieve and silica gel, which neither adsorbs nor outgases nitrogen, oxygen, or argon, provides a simple and inexpensive way to minimize glass deflection .

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3. Potential System Failures

Richard Hage

3.1 Methodology for Capturing Failure Mode Knowledge

There are two general aspects to this work. First the relevant failure events must be identified and their interrelationships captured. Secondly, the mechanisms of the identified failure events must be understood with consideration to both theoretical and practical concerns. This section discusses the approach to primarily address the first of these tasks. The approach outlined also provides the framework for bounding the questions of the latter task.

Two tools were chosen for their utility towards identifying and capturing the relevant failure events. They are Failure Modes and Effects Analysis (FMEA) and Event tree diagrams. The FMEA functions as both a conversation tool and a documentation tool for capturing the failure possibilities of a system. Event tree diagrams and fault tree diagrams are graphical means for representing the chain of events which can ultimately lead to product failure. The diagrams employ information generated from an FMEA.

Documenting the failure events in such a manner is of great importance to the industry as a whole. It is important to spacer system manufacturers as well as insulated glass manufacturers as it provides guidance to both the design and process which must be established and maintained to ensure installed spacer systems result in highly durable IG units.

FMEA is a communication and documentation tool. An example FMEA for the box spacer system is shown in Figure 3-5. It is intended to capture existing knowledge regarding the failure potential of proposed or existing product. It facilitates communication of knowledge by drawing thoughts from a multi-disciplinary team of experts [1].

The format into which the FMEA is captured consists of the following entries [2]:

- Product functions
- Failure modes
- Effects
- Causes
- Controls
- Severity of Effect
- Probability of Occurrence
- Probability of Detection

When developing the FMEA it is necessary to determine from whose perspective the product failure is viewed. The sense of perspective is often referred to as the "target" of the FMEA. The target can be the end consumer, the design team, the manufacturing center, or any number of individual or corporate entities. By defining the target, the definition of functions, failure modes and effects will all be more consistently and usefully defined. The target for this current effort was chosen to be the end consumer. This target makes sense as it is the perceptions of the end consumer which will determine whether or not a product is viewed as satisfactorily durable. FMEA entries are thus being developed with this target in mind.

Product functions are the capabilities which a product must satisfactorily provide in order for it to be viewed as a successful product. The functions are expressed in terms of attributes which are desirable to the target, or end consumer. Common functions required by the consumer are as follows:

- Maintain optimum U-value
- Maintain optimum Solar Heat Gain Coefficient
- Allow no internal condensation
- Allow no glass cracks
- Seal house interior from outdoors

Alternatively, internal condensation could be captured under an effect title such as “provide transparent view to outdoors”. Glass cracking and other appearance degradation issues could be captured under an effect title such as “maintain aesthetic appearance”.

Failure modes are representative categories which define a product failure. They represent the means by which driving causes reach expression as failure. For the purposes of this effort it is useful to think of how individual IG components experience failure. The boundary of components is also considered. A representative, but not exhaustive list, of failure modes used for IG discussion is shown below.

- MVTR seal cohesive failure due to tension or compression
- Structural sealant shear stress failure
- MVTR seal adhesion loss at glass
- Spacer structural failure
- Desiccant saturation
- Total Glass structural failure

Causes are the perturbations of a system which cause a failure mode to occur; they can be any perturbing stress, including but not limited to environmental stressors, process inconsistencies, material flaws, and design weaknesses. During FMEA construction it is often a challenge to determine how deeply to delve into the cause of a failure. For instance, degradation due to solar exposure could be defined at a more macro level as caused by UV exposure. At the extreme depth of detail, the cause could be defined as initiating when photons are emitted. To support a useful FMEA it is useful to define the cause at a level which is actionable by methods of process or design detection. In the example, UV exposure would be chosen as the proper level of detail, as it is a quantity which can be measured and whose impact on the product is understood to some resolution.

Often FMEAs are performed independently for two classes of product issues: design related and process related. For the purpose of this effort it was found that the failure modes identified could in many cases be attributable to a multitude of either process or design issues. Whereas the causes were unique in that they were driven by either process or design issues, the resulting failure modes and their effects were common to the two cause regimes. Thus the failure mode and effect framework was found to be applicable for both process and design issues. The two different cause classes are captured within this framework by attributing them to design or process issues.

Examples of design related causes which lead to the failure mode of a structural sealant cohesive failure due to tension and compression are:

- Cyclic dishing fatigue
- High internal IG pressure
- UV embrittlement/cracking
- Chemical degradation

Examples of process related causes which lead to the structural sealant cohesive failure mode are:

- Improper applied thickness
- Process contamination
- Improper formulation
- Load excedence before cure
- Improper application
- Internal voids due to process

Effects are the observable outcomes of failure modes. In developing the effects it is especially necessary to view the FMEA from the target's perspective. For the current effort, effects are the outcomes which result in some degree of displeasure to the end consumer. This end consumer could be a private homeowner or a commercial businessman. Some undesirable effects, from the end consumer's perspective, that are captured for the current effort are as follows:

- Internal condensation
- Loss of U-value
- Poor aesthetics
- Visible glass crack
- House open to outdoors
- Glass dishing
- Glass collapse

Controls are the procedures in place which are designed to capture faulty product. The controls are in many cases on-line process checks which are used during production to ensure quality product. The control procedures are not limited to on-line checks, however, vendor checks and milestone observations are also among valid controls alternatives. The types of control are somewhat driven by whether the failures are design driven or process driven. For process driven causes, potential controls could be, among others:

- Monitor process with SPC charts
- Incoming vendor inspection
- Automated on-line tolerance checks

Design driven causes may also involve such on-line inspections, but they may also involve a variety of screening tests and design tools. Often engineering rules of thumb and physical models will drive assessments. These will be considered controls as well, as when used properly they can eliminate the occurrence of the cause-failure-effect chain. Some examples of controls used to address design driven causes are as follows:

- Physics based mathematical modeling
- Stress exposure testing
- Accelerated testing
- Field Weathering
- Component level validation tests

The FMEA provides a means to capture the current understanding of which failure modes may occur, how they are caused, and what their effect will be. It also provides a means to capture current understanding of the severity of the effects, the probability of occurrence of the cause-failure-effect chain, and the likelihood of detecting the cause-failure effect chain. These ratings are developed using numeric values which are accepted by the FMEA team.

The severity rating is a quantitative measure of how detrimental a failure mode's effect is from the target's viewpoint. The severity scale used for the purpose of the IG effort is shown in Figure 3-1. The low extreme of the scale is no noticeable problem. The high extreme of the scale represents issues of safety and corporate brand erosion.

Severity (1-10)	*Severity of the Failure Mode's Effect*
1	Effect exists, but is not noticeable
3	Customer inconvenience,but does not seek service
5	Customer annoyance/Service call likely
9	Person injury/ Severe dissatisfaction with product
10	Severe personal injury/Brand erosion

Figure 3-1. Severity rating scale

The probability of occurrence rating is a quantitative measure of the probability of the entire cause-failure-effect chain occurring. It is important to view the entire cause to effect chain when developing this ranking, because within a failure mode category there are often several effects as well as several causes. By providing the probability of occurrence of the entire chain of events, this rating can be performed to the resolution of the specific causes, which is generally a tighter resolution than if only a failure mode category is considered. The degree of resolution and validity of the probability estimate is limited by the degree of a priori design knowledge available. For the purposes of the IG durability assessment, the scale shown in Figure 3-2 was used. The extreme low end of the scale, a probability of zero, can be used if the systems physics dictate that no failure is possible. The next highest rating of one in a million is thought to capture failures which may only manifest themselves in a handful of units from an entire population. The highest rating represents convergence on failures which are approaching probable.

Occurrence (0-10)	*Probability of the Cause-Failure-Effect Chain Occurring*
0	physically impossible
1	1 in 1 million
2	1 in 500,000
3	1 in 100,000
4	1 in 50,000
5	1 in 10,000
6	1 in 5,000
7	1 in 1,000
8	1 in 100
9	1 in 10
10	1 in 2

Figure 3-2. Probability of Occurrence rating scale

The probability of detection is a quantitative ranking which refers to the likelihood of detecting the cause-failure-effect chain of events. This rating is the exception to target perspective. This rating value differs from severity and probability of occurrence in that it is viewed from the producer's rather than the consumer's perspective. It represents the probability the potential or realized failure mode can be detected before it gets to the customer. The rank value for detection is higher for lower probabilities of detection. It is phrased in this manner because the purpose of an FMEA is to support minimization of observed product failure in the field. If a failure is unlikely to be detected, a high rating value will raise flags to indicate that greater thought must be given to catching these potential failures before they happen. The probability of detection scale used for the purposes of this effort is shown in Figure 3-3.

Detection (1-10)	*Likelihood of Detecting Cause-Failure-Effect Chain*
1	100%, Certain to detect
2	90%
3	80%
4	70%
5	60%
6	50%
7	40%
8	30%
9	20%
10	<10%, Very difficult to detect

Figure 3-3. Probability of Detection rating scale

The event tree technique is a method for representing system failures which occur as a result of interrelated chain event subsystem failures [3]. Systems which have subsystem failures which are not interrelated are represented more easily by block diagram representations. Electronic systems often lend themselves to block diagrams since the failure rates of individual components are independent of the failures of neighboring components. Mechanical systems, however, are often best represented by event trees, due to the complex interactions of stress and strains among neighboring components [4].

As a complex mechanical system, Insulated Glass units are best represented by event trees. An example of such an event tree representation is shown in Figure 3-14. The benefits of using the event tree diagram are two-fold. First it allows a graphical representation of the chain of events which must occur in order for a failure to occur. Second it provides the logical framework from which system simulation assessment studies can be performed.

The event tree is especially useful in the present effort as it allows both the similarities and the differences of each IG spacer design class to be seen clearly. Although the FMEA captures the same information, it does not as clearly show the interdependencies among the failure modes. The event tree shows how the failure modes captured within the FMEA interact to result in product failure. Similarities and differences in the failure mode blocks and similarities and differences within the failure mode interactions are captured. The failure modes and resulting effects identified within the FMEA are captured in this construct for each design class.

The unique tree for each design class is also beneficial as it ties together the technical discussions developed for each of the failure mode blocks. The failure modes are one area of commonality across many of the IG design classes. In many cases, it is not so much the differences within these failure modes which is significant, but how they all interact to result in system failure.

The overall event tree thus captures the failure mode interactions and the effects of system failure. The individual causes, identified in the FMEA, for each failure mode are captured by using a different construct, which is a fault tree rather than event tree. An example fault tree construct for a failure mode block is shown in Figure 3-19.

A fault tree rather than an event tree is appropriate for representing the failure mode causes, because it is constructed to outline the logic that must occur for a specific failure to occur [3]. This differs from an event tree, which shows the failure paths which lead to a multitude of failures. For each failure mode, a failure is designated to occur if any of the identified causes occurs. The causes are categorized in terms of both design related causes and process related causes. The fault tree is constructed to capture causes, in concert with the event tree for capturing failure modes and effects. Together the event trees and fault trees are a necessary and effective means of communicating the understanding generated from the FMEA.

Notes Regarding Application of IG FMEA and Event Trees

In order to effectively support proper design and process guidance for the IG industry, the FMEAs and Event Trees must be accurate representations of reality. This accuracy can only be insured if the underlying principles are understood and captured and if the practical design and process issues are sufficiently captured.

This required accuracy can be obtained if the FMEA and Event trees are developed from first principle levels and then submitted for review by the industry. The first principle FMEAs and Event Trees can then be updated by incorporating the practical and theoretical observations from spacer system manufacturers and IG manufacturers. It is particularly important to capture the perceived probability of occurrence, severity, and probability of detection from the industry's perspective. Also it is important to receive industry input regarding currently utilized controls for the process.

The FMEA is the tool for encouraging and capturing this dialogue. If this information is captured to sufficient resolution, with a view to practical considerations, it will provide a useful reference body of knowledge for the IG industry.

The FMEAs and Event Trees presented within this paper are draft documents which have been developed from first principles by a team of Aspen Research associates. The documents are available for review by IG industry. Industry feedback has been actively solicited. Some initial feedback has been obtained from industry and this information has been captured as appropriate. The FMEAs are evolving documents which become more useful and accurate as additional industry feedback is obtained. Initial feedback has indicated that the first draft FMEAs and Event Trees are reasonable first cut approximations.

The presented FMEAs do not include values in the severity, probability of occurrence, or detecting rating scales. This is purposeful, as providing estimates for these ratings will constitute a quantitative assessment. The proposed second phase of this effort will involve quantifying estimates of these ratings, in addition to other proposed quantitative activities. As the FMEAs exist, without the ratings, they are already a template upon which industry can develop understanding of core process and design issues.

It should finally be noted that the FMEA deal specifically with design and process causes of failure. It is plausible that failure causes exist at other points in the IG life cycle process. For instance, an IG may be design and processed properly for its intended environment, only to be improperly specified for installation in an application beyond its design capabilities. Also, miscommunication about warranty policies may result in replacement of units which are performing satisfactorily. These application issues were beyond the scope of this initial FMEA, however, in future efforts the FMEA concept could be applied to capture these issues within specification, distribution, and warranty policy FMEAs.

3.2 Box Spacer System FMEA

The box spacer system design class, shown in Fig. 3-4, was assessed with a team of Aspen associates. The resulting Failure Modes and Effects Analysis template generated is shown in Fig. 3-5.

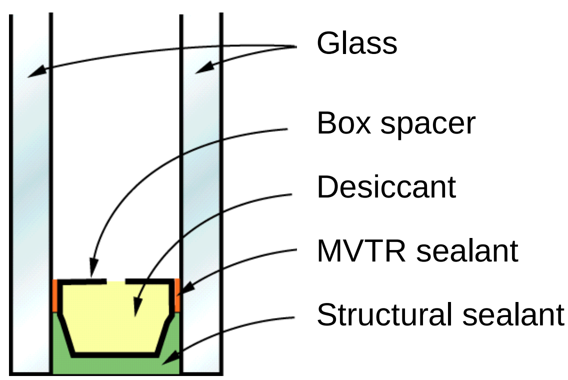


Figure 3-4. Box Spacer System Design Class

Figure 3-5. FMEA for the Box Spacer System Design Class

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors 2. Provide Optimum Thermal Efficiency 3. Maintain Aesthetic Appearance	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling & Exposure tests	?
		Poor SHGC	?	High internal IG pressure	?	Modeling & Exposure tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure tests	?
				Chemical Degradation	?	Modeling & Exposure tests	?
				Doesn't meet pressure requirements	?	Modeling & Exposure tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Improper Glass to Spacer COTE match	?	Modeling & Exposure tests	?
		Poor SHGC	?	Doesn't meet static load requirements	?	Modeling & Exposure tests	?
				Chemical Degradation	?	Modeling & Exposure tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Unsupported pane	?	Install inspection	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR & Structural Seal Adhesion Loss at Glass	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Delamination of sputter coated layers	?	Modeling & Exposure tests	?
		Poor SHGC	?	Cyclic Dishing Fatigue	?	Modeling & Exposure tests	?
				High internal IG pressure	?	Modeling & Exposure tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure tests	?
				Chemical Degradation	?	Modeling & Exposure tests	?
				Process			
				Skips during application	?	Monitor Process	?
				Improper assembly pressure	?	Monitor Process	?
				Improper coating deletion	?	Monitor Process	?
				Improper assembly thermal conditions	?	Monitor Process	?
				Process contaminant at interface	?	Monitor Process	?
				Improper applied thickness	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Voids at interface due to application	?	Monitor Process	?
	MVTR & Structural Seal Adhesion Loss at Spacer	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling & Exposure tests	?
		Poor SHGC	?	High internal IG pressure	?	Modeling & Exposure tests	?
				Inadequate sealant strength for design	?	Modeling & Exposure tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure tests	?
				Chemical Degradation	?	Modeling & Exposure tests	?
				Process			
				Process contaminant at interface	?	Monitor Process	?
				Improper assembly pressure	?	Monitor Process	?
				Improper assembly thermal conditions	?	Monitor Process	?
				Improper applied thickness	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Skips during application	?	Monitor Process	?
				Voids at interface due to application	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors	Spacer Structural Failure	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Manufacturing Defect	?	Monitor Vendor/Process	?
2. Provide Optimum Thermal Efficiency		Poor SHGC	?	Metal defect from roll forming	?	Monitor Vendor/Process	?
				Collapse at corner bend	?	Monitor Process	?
3. Maintain Aesthetic Appearance	Dessicant Saturation	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Inadequate Seal MVTR	?	Modeling & Exposure tests	?
(continued)		Poor SHGC	?	**Process**			
				Insufficient Desiccant	?	Monitor Process	?
				Improper Dessicant	?	Monitor Vendor/Process	?
				Saturation during storage	?	Monitor Process	?
	Incomplete Glass Structural Failure	Visible glass crack	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	Total Glass Structural Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	Argon Loss	Glass Collapse	?	**Design**			
		Loss of U-Value	?	Improper sealant specified	?	Modeling & Exposure tests	?
		Poor SHGC	?	UV degradation	?	Modeling & Exposure tests	?
				Chemical degradation	?	Modeling & Exposure tests	?
				Process			
				Formulation inconsistency	?	Monitor Vendor/Process	?
				Improper application	?	Monitor Process	?
				Leak path from IG	?	Monitor Process	?
	Pressure, Temp Delta Deflection	Glass Dishing	?	**Design**			
		Loss of U-Value	?	Insufficient stiffness	?	Modeling & Exposure tests	?
		Poor SHGC	?				
	Too much air adsorption	Glass Dishing/Collapse	?	**Process**			
		Loss of U-Value	?	Too much dessicant	?	Monitor Process	?
		Poor SHGC	?	Incorrectly specified desiccant pore size	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
Isolate Living Space from Outdoors	Total Glass Structural Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	IG to Frame Sealant Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper matching of frame to IG COTE	?	Modeling & Exposure tests	?
		Poor SHGC	?	Doesn't meet pressure requirements	?	Modeling & Exposure tests	?
				Process			
				Improper sealing at assembly	?	Monitor Process	?
Allow Installation	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Shear on glazing panes at install	?	Monitor Install	?
		Poor SHGC	?	Shear on spacer at install	?	Monitor Install	?
	MVTR & Structural Seal Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	MVTR & Structural Seal Adhesion Loss at Spacer	Internal Condensaton	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	Spacer Structural Failure	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Manufacturing Defect	?	Monitor Install/Process	?
		Poor SHGC	?	Compression on spacer at install	?	Monitor Install/Process	?
	Incomplete Glass Structural Failure	Visible crack	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	Impact damage during installation	?	Monitor Install	?
	Total Glass Structural Failure	House open to outdoors	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	Impact damage during installation	?	Monitor Install	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
Allow Transport to Install Site	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Shear on glazing panes during transport	?	Pre and post inspection	?
		Poor SHGC	?	Shear on spacer during transport	?	Pre and post inspection	?
	MVTR & Structural Seal Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	MVTR & Structural Seal Adhesion Loss at Spacer	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	Spacer Structural Failure	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Manufacturing Defect	?	Monitor Vendor/Process	?
		Poor SHGC	?	Compression on spacer during transport	?	Pre and post inspection	?
	Incomplete Glass Structural Failure	Visible crack	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	Impact damage during transport	?	Pre and post inspection	?
	Total Glass Structural Failure	House open to outdoors	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	Impact damage during transport	?	Pre and post inspection	?

3.3 U Channel Spacer System FMEA

The U channel spacer system design class, shown in Fig. 3-6, was assessed with a team of Aspen associates. The resulting Failure Modes and Effects Analysis template generated is shown in Fig. 3-7.

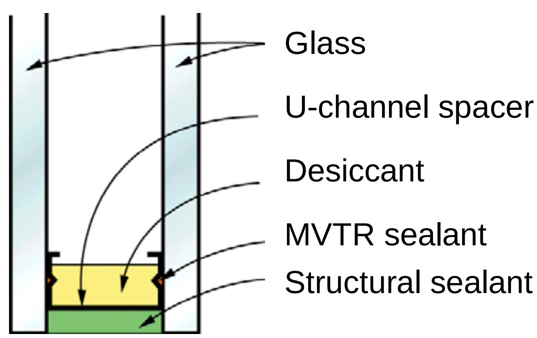


Figure 3-6. U Channel Spacer System Design Class

Figure 3-7. FMEA for the U Channel Spacer System Design Class

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors 2. Provide Optimum Thermal Efficiency 3. Maintain Aesthetic Appearance	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
		Poor SHGC	?	High internal IG pressure	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Doesn't meet pressure requirements	?	Modeling & Exposure Tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Improper Glass to Spacer COTE match	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Doesn't meet static load requirements	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Unsupported pane	?	Install inspection	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR & Structural Seal Adhesion Loss at Glass	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Delamination of sputter coated layers	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
				High internal IG pressure	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Process			
				Skips during application	?	Monitor Process	?
				Improper assembly pressure	?	Monitor Process	?
				Process contaminant at interface	?	Monitor Process	?
				Improper assembly thermal conditions	?	Monitor Process	?
				Improper applied thickness	?	Monitor Process	?
				Improper coating deletion	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Voids at interface due to application	?	Monitor Process	?
	MVTR & Structural Seal Adhesion Loss at Spacer	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
		Poor SHGC	?	High internal IG pressure	?	Modeling & Exposure Tests	?
				Inadequate sealant strength for design	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Process			
				Process contaminant at interface	?	Monitor Process	?
				Improper assembly pressure	?	Monitor Process	?
				Improper assembly thermal conditions	?	Monitor Process	?
				Improper applied thickness	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Skips during application	?	Monitor Process	?
				Voids at interface due to application	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors	Spacer Structural Failure	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Compression buckling	?	Modeling & Exposure Tests	?
2. Provide Optimum Thermal Efficiency		Poor SHGC	?	Cyclic fatigue	?	Modeling & Exposure Tests	?
				Process			
3. Maintain Aesthetic Appearance				Manufacturing Defect	?	Monitor Vendor/Process	?
				Metal defect from roll forming	?	Monitor Vendor/Process	?
(continued)				Collapse at corner bend	?	Monitor Process	?
	Inadequate Sealant MVTR	Moisture in IG	?	**Design**			
		Loss of U-Value	?	Improper sealant specified	?	Modeling & Exposure tests	?
		Poor SHGC	?	UV degradation	?	Modeling & Exposure tests	?
				Chemical degradation	?	Modeling & Exposure tests	?
				Process			
				Formulation inconsistency	?	Monitor Vendor/Process	?
				Improper application	?	Monitor Process	?
	Dessicant Saturation	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Inadequate Seal MVTR	?	Modeling & Exposure Tests	?
		Poor SHGC	?	**Process**			
				Insufficient Desiccant	?	Monitor Process	?
				Improper Dessicant	?	Monitor Vendor/Process	?
				Saturation during storage	?	Monitor Process	?
	Incomplete Glass Structural Failure	Visible glass crack	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	Total Glass Structural Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors 2. Provide Optimum Thermal Efficiency 3. Maintain Aesthetic Appearance *(continued)*	Argon Loss	Glass Collapse	?	**Design**			
		Loss of U-Value	?	Improper sealant specified	?	Modeling & Exposure tests	?
		Poor SHGC	?	UV degradation	?	Modeling & Exposure tests	?
				Chemical degradation	?	Modeling & Exposure tests	?
				Process			
				Formulation inconsistency	?	Monitor Vendor/Process	?
				Improper application	?	Monitor Process	?
				Leak path from IG	?	Monitor Process	?
	Pressure, Temp Delta Deflection	Glass Dishing	?	**Design**			
		Loss of U-Value	?	Insufficient stiffness	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Excessive temperature during sealing	?		
	Desiccant release into air space	Poor Aesthetics	?	**Design**			
				Dessicant release from Spacer	?	Modeling & Exposure Tests	?
				Desiccant particle degradation release	?	Modeling & Exposure Tests	?
	Desiccant diffusion time too slow	Loss of U-Value	?	**Design**			
		Internal Condensation	?	Slow diffusion of matrix desiccant	?	Modeling & Exposure Tests	?
				Depleted desiccant	?	Modeling & Exposure Tests	?
	Too much air adsorption	Glass Dishing/Collapse	?	**Process**			
		Loss of U-Value	?	Too much dessicant	?	Monitor Process	?
		Poor SHGC	?	Incorrectly specified desiccant pore size	?	Monitor Process	?
Isolate Living Space from Outdoors	Total Glass Structural Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	IG to Frame Sealant Failu	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper matching of frame to IG COTE	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Doesn't meet DP requirements	?	Modeling & Exposure Tests	?
				Process			
				Improper sealing at assembly	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
Allow Installation at site	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Shear on glazing panes at install	?	Monitor Install	?
		Poor SHGC	?	Shear on spacer at install	?	Monitor Install	?
	MVTR & Structural Seal Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	MVTR & Structural Seal Adhesion Loss at Spacer	Internal Condensaton	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	Spacer Structural Failure	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Manufacturing Defect	?	Monitor Install/Process	?
		Poor SHGC	?	Compression on spacer at install	?	Monitor Install/Process	?
	Incomplete Glass Structural Failure	Visible crack	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	Impact damage during installation	?	Monitor Install	?
	Total Glass Structural Failure	House open to outdoors	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	Impact damage during installation	?	Monitor Install	?
Allow Transport to Install Site	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Shear on glazing panes during transport	?	Pre and post inspection	?
		Poor SHGC	?	Shear on spacer during transport	?	Pre and post inspection	?
	MVTR & Structural Seal Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	MVTR & Structural Seal Adhesion Loss at Spacer	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	Spacer Structural Failure	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Manufacturing Defect	?	Monitor Vendor/Process	?
		Poor SHGC	?	Compression on spacer during transport	?	Pre and post inspection	?
	Incomplete Glass Structural Failure	Visible crack	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	Impact damage during transport	?	Pre and post inspection	?
	Total Glass Structural Failure	House open to outdoors	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	Impact damage during transport	?	Pre and post inspection	?

3.4 Corrugated Metal Spacer System FMEA

The corrugated metal spacer system design class, shown in Fig. 3-8, was assessed with a team of Aspen associates. The resulting Failure Modes and Effects Analysis template generated is shown in Fig. 3-9.

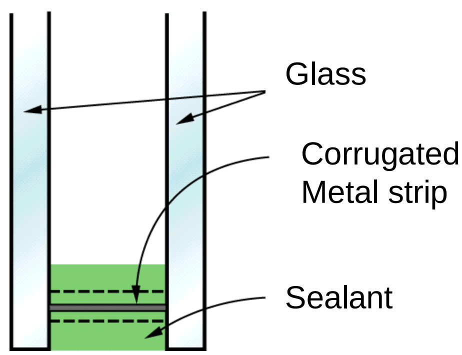


Figure 3-8. Corrugated Metal Spacer System Design Class

Figure 3-9. FMEA for the Corrugated Metal Spacer System Design Class

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors 2. Provide Optimum Thermal Efficiency 3. Maintain Aesthetic Appearance	MVTR Sealant Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
		Poor SHGC	?	High internal IG pressure	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Doesn't meet pressure required	?	Modeling & Exposure Tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR Sealant Cohesive Failure due to Shear	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Improper Glass to Spacer COTE match	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Doesn't meet static load requirements	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Unsupported pane	?	Install inspection	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR Sealant Adhesion Loss at Glass	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Delamination of sputter coated layers	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
				High internal IG pressure	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Process			
				Skips during application	?	Monitor Process	?
				Process contaminant at interface	?	Monitor Process	?
				Improper assembly pressure	?	Monitor Process	?
				Improper assembly thermal conditions	?	Monitor Process	?
				Improper applied thickness	?	Monitor Process	?
				Improper coating deletion	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Voids at interface due to application	?	Monitor Process	?
	MVTR Sealant Adhesion Loss at Spacer	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
		Poor SHGC	?	High internal IG pressure	?	Modeling & Exposure Tests	?
				Inadequate sealant strength for design	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Process			
				Process contaminant at interface	?	Monitor Process	?
				Improper assembly pressure	?	Monitor Process	?
				Improper assembly thermal conditions	?	Monitor Process	?
				Improper applied thickness	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Skips during application	?	Monitor Process	?
				Voids at interface due to application	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors 2. Provide Optimum Thermal Efficiency 3. Maintain Aesthetic Appearance *(continued)*	Spacer Structural Failure	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Manufacturing Defect	?	Monitor Vendor/Process	?
		Poor SHGC	?	Metal defect from roll forming	?	Monitor Vendor/Process	?
				Collapse at corner bend	?	Monitor Process	?
	Inadequate Sealant MVTR	Moisture in IG	?	**Design**			
		Loss of U-Value	?	Improper sealant specified	?	Modeling & Exposure tests	?
		Poor SHGC	?	UV degradation	?	Modeling & Exposure tests	?
				Chemical degradation	?	Modeling & Exposure tests	?
				Process			
				Formulation inconsistency	?	Monitor Vendor/Process	?
				Improper application	?	Monitor Process	?
	Dessicant Saturation	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Inadequate Seal MVTR	?	Modeling & Exposure Tests	?
		Poor SHGC	?	**Process**			
				Insufficient Desiccant	?	Monitor Process	?
				Improper Dessicant	?	Monitor Vendor/Process	?
				Saturation during storage	?	Monitor Process	?
	Dessicant release into air space	Poor Aesthetics	?	**Design**			
				Dessicant release from Spacer	?	Modeling & Exposure Tests	?
				Desiccant particle degradation release	?	Modeling & Exposure Tests	?
	Incomplete Glass Structural Failure	Visible glass crack	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	Total Glass Structural Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors 2. Provide Optimum Thermal Efficiency 3. Maintain Aesthetic Appearance *(continued)*	Argon Loss	Glass Collapse	?	**Design**			
		Loss of U-Value	?	Improper sealant specified	?	Modeling & Exposure tests	?
		Poor SHGC	?	UV degradation	?	Modeling & Exposure tests	?
				Chemical degradation	?	Modeling & Exposure tests	?
				Process			
				Formulation inconsistency	?	Monitor Vendor/Process	?
				Improper application	?	Monitor Process	?
				Leak path from IG	?	Monitor Process	?
	Pressure, Temp Delta Deflection	Glass Dishing	?	**Design**			
		Loss of U-Value	?	Insufficient stiffness	?	Modeling & Exposure Tests	?
		Poor SHGC	?				
	Too much air adsorption	Glass Dishing/Collapse	?	**Process**			
		Loss of U-Value	?	Too much dessicant	?	Monitor Process	?
		Poor SHGC	?	Incorrectly specified desiccant pore size	?	Monitor Process	?
Isolate Living Space from Outdoors	Total Glass Structural Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	IG to Frame Sealant Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper matching of frame to IG COTE	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Doesn't meet pressure requirements	?	Modeling & Exposure Tests	?
				Process			
				Improper sealing at assembly	?	Monitor Process	?
Allow Installation	MVTR Sealant Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	MVTR Sealant Cohesive Failure due to Shear	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Shear on glazing panes at install	?	Monitor Install	?
		Poor SHGC	?	Shear on spacer at install	?	Monitor Install	?
	MVTR & Structural Seal Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	MVTR & Structural Seal Adhesion Loss at Spacer	Internal Condensaton	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	Spacer Structural Failure	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Manufacturing Defect	?	Monitor Install/Process	?
		Poor SHGC	?	Compression on spacer at install	?	Monitor Install/Process	?
	Incomplete Glass Structural Failure	Visible crack	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	Impact damage during installation	?	Monitor Install	?
	Total Glass Structural Failure	House open to outdoors	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	Impact damage during installation	?	Monitor Install	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
Allow Transport to Install Site	MVTR Sealant Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	MVTR Sealant Cohesive Failure due to Shear	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Shear on glazing panes during transport	?	Pre and post inspection	?
		Poor SHGC	?	Shear on spacer during transport	?	Pre and post inspection	?
	MVTR & Structural Seal Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	MVTR & Structural Seal Adhesion Loss at Spacer	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	Spacer Structural Failure	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Manufacturing Defect	?	Monitor Vendor/Process	?
		Poor SHGC	?	Compression on spacer during transport	?	Pre and post inspection	?
	Incomplete Glass Structural Failure	Visible crack	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	Impact damage during transport	?	Pre and post inspection	?
	Total Glass Structural Failure	House open to outdoors	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	Impact damage during transport	?	Pre and post inspection	?

3.5 Thermoplastic Spacer System FMEA

The thermoplastic spacer system design class, shown in Fig. 3-10, was assessed with a team of Aspen associates. The resulting Failure Modes and Effects Analysis template generated is shown in Fig. 3-11.

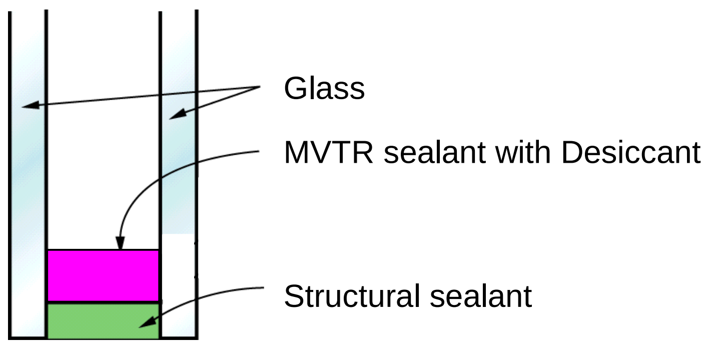


Figure 3-10. Thermoplastic Spacer System Design Class

Figure 3-11. FMEA for the Thermoplastic Spacer System Design Class

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors 2. Provide Optimum Thermal Efficiency 3. Maintain Aesthetic Appearance	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
		Poor SHGC	?	High internal IG pressure	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Doesn't meet pressure required	?	Modeling & Exposure Tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Improper Glass to Spacer COTE match	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Doesn't meet static load requirements	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Unsupported pane	?	Install inspection	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR Adhesion Loss at Glass	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Delamination of sputter coated layers	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
				High internal IG pressure	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Process			
				Skips during application	?	Monitor Process	?
				Improper assembly pressure	?	Monitor Process	?
				Process contaminant at interface	?	Monitor Process	?
				Improper assembly thermal conditions	?	Monitor Process	?
				Improper applied thickness	?	Monitor Process	?
				Improper coating deletion	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Voids at interface due to application	?	Monitor Process	?
	Inadequate Sealant MVTR	Moisture in IG	?	**Design**			
		Loss of U-Value	?	Improper sealant specified	?	Modeling & Exposure tests	?
		Poor SHGC	?	UV degradation	?	Modeling & Exposure tests	?
				Chemical degradation	?	Modeling & Exposure tests	?
				Process			
				Formulation inconsistency	?	Monitor Vendor/Process	?
				Improper application	?	Monitor Process	?
	Dessicant Saturation	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Inadequate Seal MVTR	?	Modeling & Exposure Tests	?
		Poor SHGC	?	**Process**			
				Insufficient Desiccant	?	Monitor Process	?
				Improper Dessicant	?	Monitor Vendor/Process	?
				Saturation during storage	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors 2. Provide Optimum Thermal Efficiency 3. Maintain Aesthetic Appearance *(continued)*	Desiccant diffusion time too slow	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Slow diffusion of embedded desiccant	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Depleted Desiccant	?	Modeling & Exposure Tests	?
	Incomplete Glass Structural Failure	Visible glass crack	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	Total Glass Structural Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	Argon Loss	Glass Collapse	?	**Design**			
		Loss of U-Value	?	Improper sealant specified	?	Modeling & Exposure tests	?
		Poor SHGC	?	UV degradation	?	Modeling & Exposure tests	?
				Chemical degradation	?	Modeling & Exposure tests	?
				Process			
				Formulation inconsistency	?	Monitor Vendor/Process	?
				Improper application	?	Monitor Process	?
				Leak path from IG	?	Monitor Process	?
	Pressure, Temp Delta Deflection	Glass Dishing	?	**Design**			
		Loss of U-Value	?	Insufficient stiffness	?	Modeling & Exposure Tests	?
		Poor SHGC	?				
	Too much air adsorption	Glass Dishing/Collapse	?	**Process**			
		Loss of U-Value	?	Too much dessicant	?	Monitor Process	?
		Poor SHGC	?	Incorrectly specified desiccant pore size	?	Monitor Process	?
Isolate Living Space from Outdoors	Total Glass Structural Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	IG to Frame Sealant Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper matching of frame to IG COTE	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Doesn't meet pressure requirements	?	Modeling & Exposure Tests	?
				Process			
				Improper sealing at assembly	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
Allow Installation	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Shear on glazing panes at install	?	Monitor Install	?
		Poor SHGC	?	Shear on spacer at install	?	Monitor Install	?
	MVTR Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	Incomplete Glass Structural Failure	Visible crack	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	Impact damage during installation	?	Monitor Install	?
	Total Glass Structural Failure	House open to outdoors	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	Impact damage during installation	?	Monitor Install	?
Allow Transport to Install Site	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Shear on glazing panes during transport	?	Pre and post inspection	?
		Poor SHGC	?	Shear on spacer during transport	?	Pre and post inspection	?
	MVTR Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	Incomplete Glass Structural Failure	Visible crack	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	Impact damage during transport	?	Pre and post inspection	?
	Total Glass Structural Failure	House open to outdoors	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	Impact damage during transport	?	Pre and post inspection	?

3.6 Non-Rigid Barrier Spacer System FMEA

The non-rigid barrier spacer system design class, shown in Fig. 3-12, was assessed with a team of Aspen associates. The resulting Failure Modes and Effects Analysis template generated is shown in Fig. 3-13.

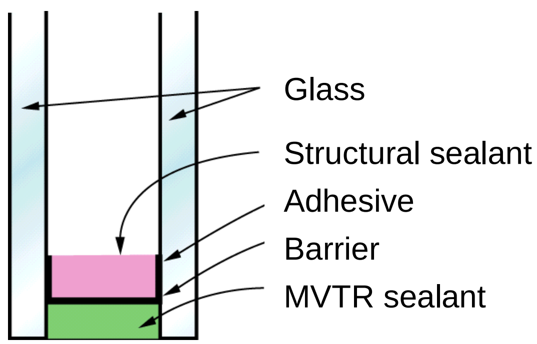


Figure 3-12. Non-rigid Barrier Spacer System Design Class

Figure 3-13. FMEA for the Non-rigid Barrier Spacer System Design Class

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors 2. Provide Optimum Thermal Efficiency 3. Maintain Aesthetic Appearance	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
		Poor SHGC	?	High internal IG pressure	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Doesn't meet pressure requirements	?	Modeling & Exposure Tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Improper Glass to Spacer COTE match	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Doesn't meet static load requirements	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Unsupported pane	?	Install inspection	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR Adhesion Loss at Glass	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Delamination of sputter coated layers	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
				Inadequate sealant strength for design	?	Modeling & Exposure Tests	?
				High internal IG pressure	?	Modeling & Exposure Tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Process			
				Skips during application	?	Monitor Process	?
				Improper assembly pressure	?	Monitor Process	?
				Improper assembly thermal conditions	?	Monitor Process	?
				Improper applied thickness	?	Monitor Process	?
				Process contaminant at interface	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Voids at interface due to application	?	Monitor Process	?
	Structural Sealant Adhesion Loss at Barrier	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
		Poor SHGC	?	UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Process			
				Process contaminant at interface	?	Monitor Process	?
				Skips during application	?	Monitor Process	?
				Improper assembly pressure	?	Monitor Process	?
				Improper assembly thermal conditions	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Voids at interface due to application	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors	Barrier Adhesion Loss at Glass	Internal Condensation	?	**Design**			
2. Provide Optimum Thermal Efficiency		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling & Exposure Tests	?
3. Maintain Aesthetic Appearance		Poor SHGC	?	High internal IG pressure	?	Modeling & Exposure Tests	?
(continued)				UV Embrittlement/Cracking	?	Modeling & Exposure Tests	?
				Chemical Degradation	?	Modeling & Exposure Tests	?
				Process			
				Process contaminant at interface	?	Monitor Process	?
				Delamination of sputter coated layers	?	Monitor Process	?
				Skips during application	?	Monitor Process	?
				Improper assembly pressure	?	Monitor Process	?
				Improper assembly thermal conditions	?	Monitor Process	?
				Improper applied thickness	?	Monitor Process	?
				Improper coating deletion	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor/Process	?
				Load Exceedence before cured	?	Monitor Process	?
				Voids at interface due to application	?	Monitor Process	?
	Barrier Cohesive Failure	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Tension/compression induced tearing	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Shear induced tearing	?	Modeling & Exposure Tests	?
				Tension/compress induced delamination	?	Modeling & Exposure Tests	?
				Shear induced delamination	?	Modeling & Exposure Tests	?
	Barrier Porosity	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Improper application	?	Monitor Process	?
		Poor SHGC	?	Material defect	?	Monitor Vendor/Process	?
	Inadequate Sealant MVTR	Moisture in IG	?	**Design**			
		Loss of U-Value	?	Improper sealant specified	?	Modeling & Exposure tests	?
		Poor SHGC	?	UV degradation	?	Modeling & Exposure tests	?
				Chemical degradation	?	Modeling & Exposure tests	?
				Process			
				Formulation inconsistency	?	Monitor Vendor/Process	?
				Improper application	?	Monitor Process	?
	Dessicant Saturation	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Inadequate Seal MVTR	?	Modeling & Exposure Tests	?
		Poor SHGC	?	**Process**			
				Insufficient Desiccant	?	Monitor Process	?
				Improper Dessicant	?	Monitor Vendor/Process	?
				Saturation during storage	?	Monitor Process	?
	Desiccant diffusion time too slow	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Slow diffusion of embedded desiccant	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Depleted desiccant	?	Modeling & Exposure Tests	?
	Incomplete Glass Structural Failure	Visible glass crack	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors 2. Provide Optimum Thermal Efficiency 3. Maintain Aesthetic Appearance *(continued)*	Total Glass Structural Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	Argon Loss	Glass Collapse	?	**Design**			
		Loss of U-Value	?	Improper sealant specified	?	Modeling & Exposure tests	?
		Poor SHGC	?	UV degradation	?	Modeling & Exposure tests	?
				Chemical degradation	?	Modeling & Exposure tests	?
				Process			
				Formulation inconsistency	?	Monitor Vendor/Process	?
				Improper application	?	Monitor Process	?
				Leak path from IG	?	Monitor Process	?
	Pressure, Temp Delta Deflection	Glass Dishing	?	**Design**			
		Loss of U-Value	?	Insufficient stiffness	?	Modeling & Exposure Tests	?
		Poor SHGC	?				
	Too much air adsorption	Glass Dishing/Collapse	?	**Process**			
		Loss of U-Value	?	Too much dessicant	?	Monitor Process	?
		Poor SHGC	?	Incorrectly specified desiccant pore size	?	Monitor Process	?
Isolate Living Space from Outdoors	Total Glass Structural Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper heat treat specification	?	Modeling & Exposure tests	?
		Poor SHGC	?	Improper glass to frame clearance	?	Modeling & Exposure tests	?
				Process			
				Inadequate Glass Edge Cut	?	Monitor Vendor/Process	?
				Heat treat edge defect	?	Monitor Vendor/Process	?
				Unsupported pane	?	Monitor Process	?
				Inclusion breakage	?	Monitor Vendor/Process	?
				Handling Damage	?	Monitor Process	?
				Frame load transfer	?	Verify Install	?
				Impact	?	Monitor Process	?
	IG to Frame Sealant Failure	House open to outdoors	?	**Design**			
		Loss of U-Value	?	Improper matching of frame to IG COTE	?	Modeling & Exposure Tests	?
		Poor SHGC	?	Doesn't meet pressure requirements	?	Modeling & Exposure Tests	?
				Process			
				Improper sealing at assembly	?	Monitor Process	?

Functions	Failure Modes	Effects	S	Causes	O	Control	D
Allow Installation	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Shear on glazing panes at install	?	Monitor Install	?
		Poor SHGC	?	Shear on spacer at install	?	Monitor Install	?
	MVTR & Structural Seal Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	Structural Sealant Adhesion Loss at Barrier	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	Barrier Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	Barrier Cohesive Failure	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	IG compression/tension during install	?	Monitor Install	?
	Incomplete Glass Structural Failure	Visible crack	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	Impact damage during installation	?	Monitor Install	?
	Total Glass Structural Failure	House open to outdoors	?	**Process**			
		Loss of U-Value	?	IG twist during installation	?	Monitor Install	?
		Poor SHGC	?	Impact damage during installation	?	Monitor Install	?
Allow Transport to Install Site	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Process**			
		Loss of U-Value	?	Shear on glazing panes during transport	?	Pre and post inspection	?
		Poor SHGC	?	Shear on spacer during transport	?	Pre and post inspection	?
	MVTR & Structural Seal Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	Structural Sealant Adhesion Loss at Barrier	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	Barrier Adhesion Loss at Glass	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	Barrier Cohesive Failure	Internal Condensation	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	IG compression/tension during transport	?	Pre and post inspection	?
	Incomplete Glass Structural Failure	Visible crack	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	Impact damage during transport	?	Pre and post inspection	?
	Total Glass Structural Failure	House open to outdoors	?	**Process**			
		Loss of U-Value	?	IG twist during transport	?	Pre and post inspection	?
		Poor SHGC	?	Impact damage during transport	?	Pre and post inspection	?

3.7 Event Trees for Each Design Class

Event trees were developed for each of the five design classes. The primary reference for the event trees was the FMEAs developed for each design class. Understanding of failure mechanisms was also an input reference for the event trees. Specifically, understanding of the sequential chain of events leading to system failure was captured from failure mechanism knowledge. The event trees are consistent with the data generated from the FMEAs, the same failure mode grouping is utilized. The design and process failure inducing causes are also directly tied to the recorded results of the FMEA. The perceived system failures are also consistent. The event tree differs from the FMEA in that it captures with more detail the sequence of events which must occur for a given system failure to be realized. This more thorough graphical representation of the failure chain allows greater qualitative understanding of the cause-failure-effect chain. The event tree has a second purpose in that it can support future analytical modeling of system failure events.

The following event trees are comprised of two primary structures. First, an overall event tree is provided for each design class. These overall event trees show, to the failure mode level, how the sequences of mode failures will result in system failure. The second structure is a series of subsystem fault trees for each failure mode. These subsystem fault trees diagrammatically show each of the design and process fault which can lead to a failure of the defined mode. These two structures differ in that the overall event tree shows the chain of failure modes which must occur for failure. The subsystem event trees show a logical, “or”, relationship of all the design and process causes for each failure mode. The causes are related by the “or” logic construct because any one of the causes becoming expressed will result in failure of the mode.

Of course, the subsystem fault trees are related to the failure modes within the overall event trees by the numeric tags. When developing both the FMEAs and Event trees it became apparent that there is much failure mode commonality within the design classes. Because of this commonality of failure modes, many of the same number tags, and thus subsystem event trees will be common among many design classes.

Figure 3-14. Overall Event Tree for the Box Spacer System

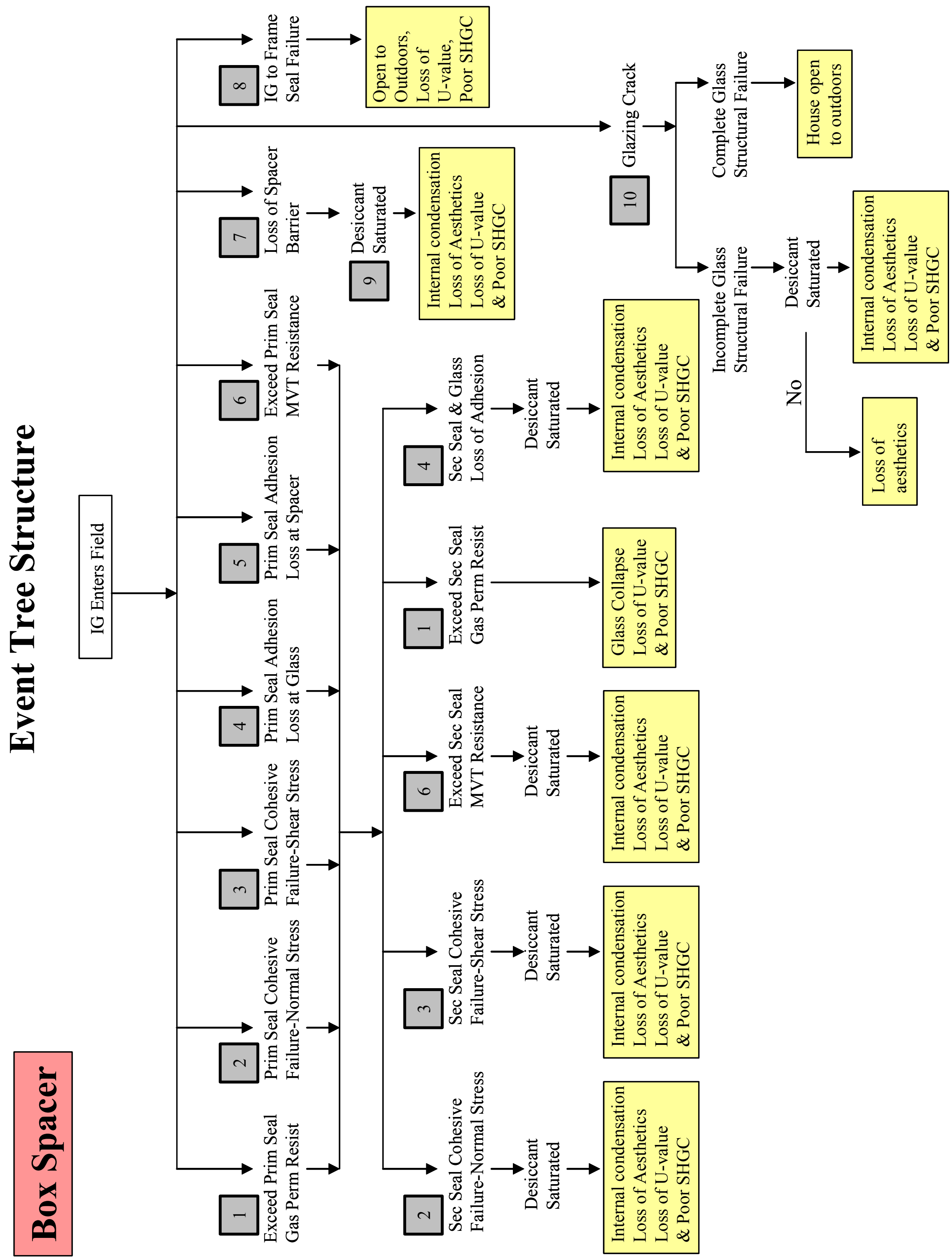


Figure 3-15. Overall Event Tree for the U Channel Spacer System

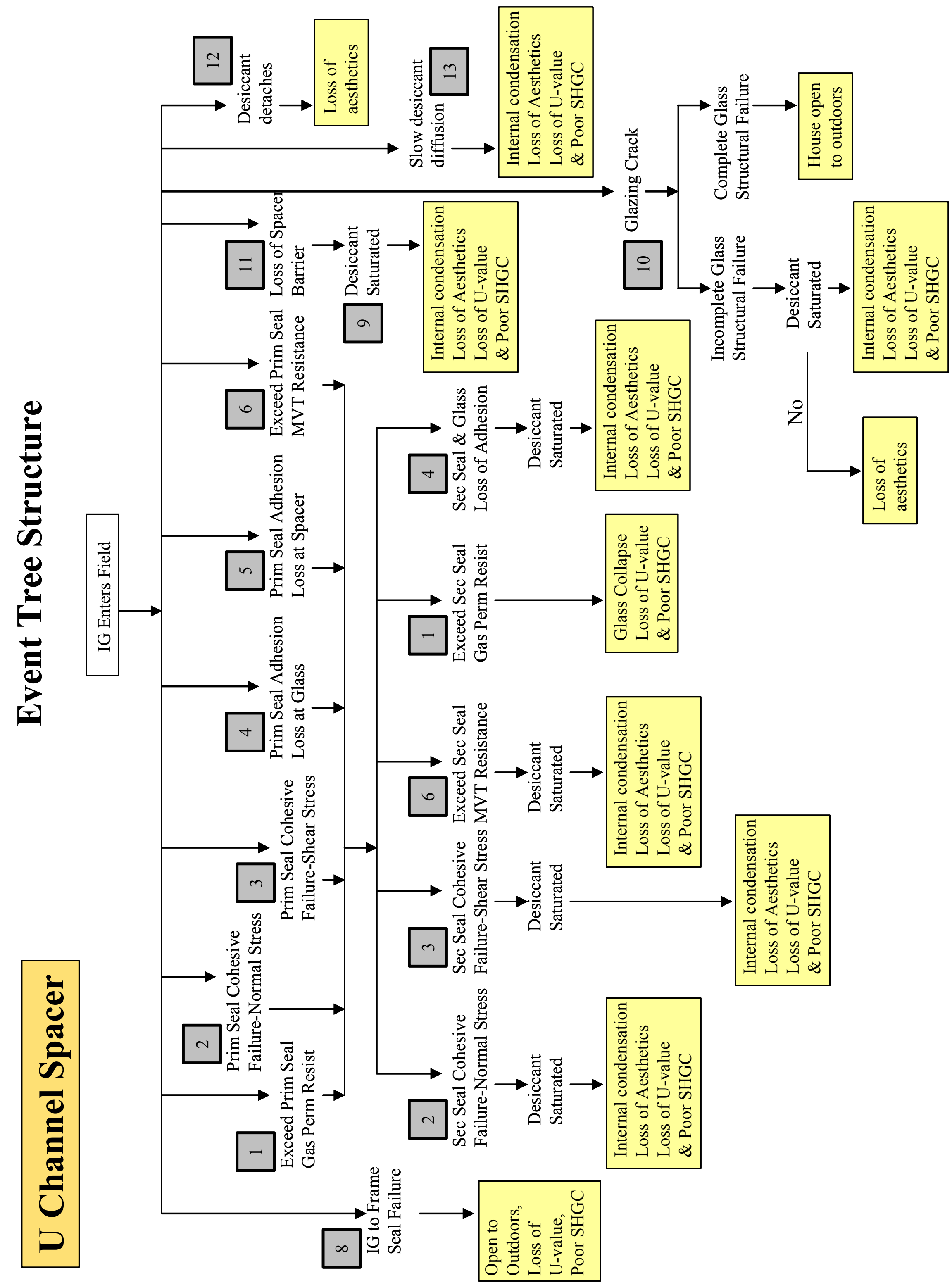


Figure 3-16. Overall Event Tree for the Corrugated Strip Spacer System

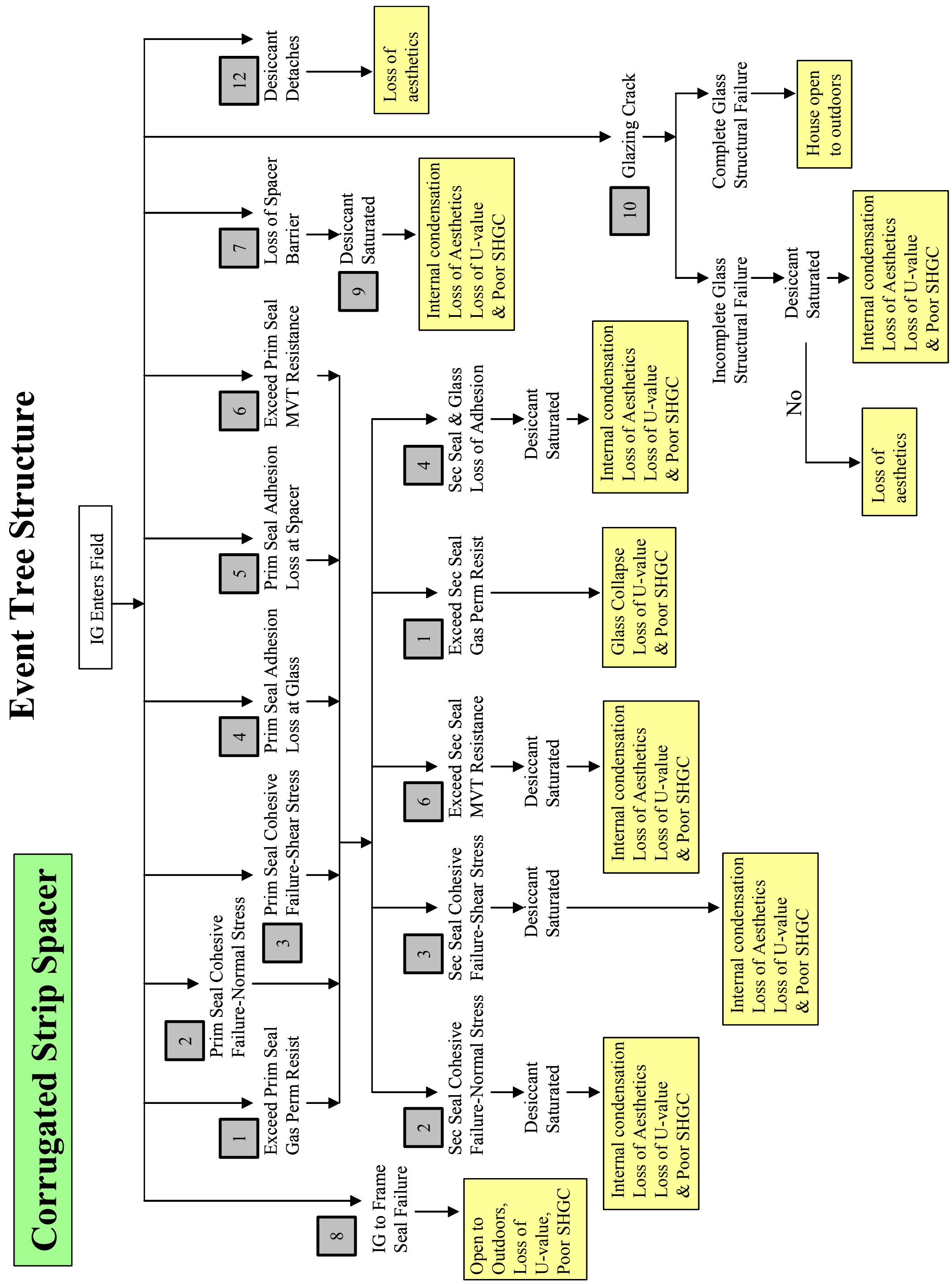


Figure 3-17. Overall Event Tree for Thermoplastic Spacer System

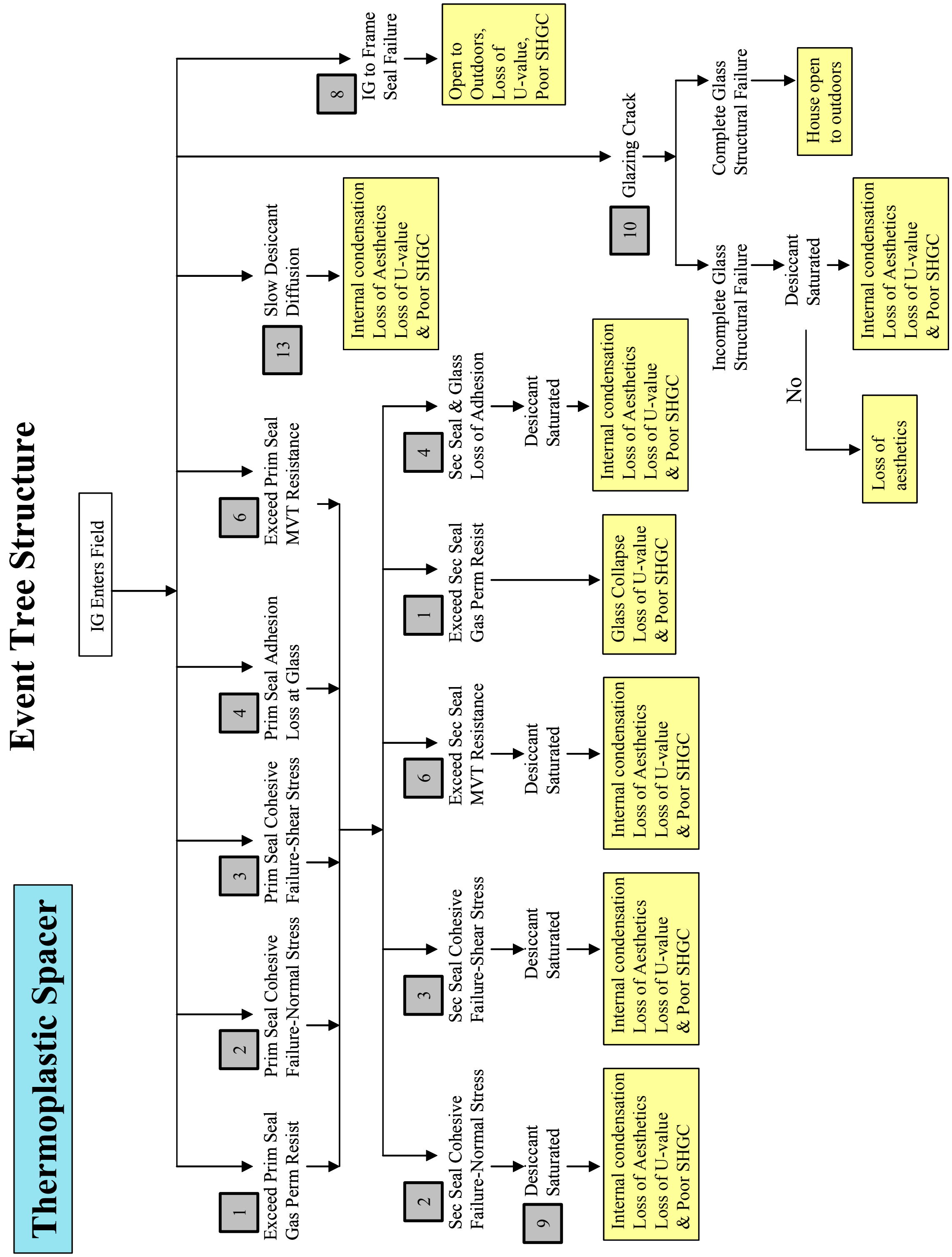


Figure 3-18. Overall Event Tree for the Non-rigid Barrier Spacer System

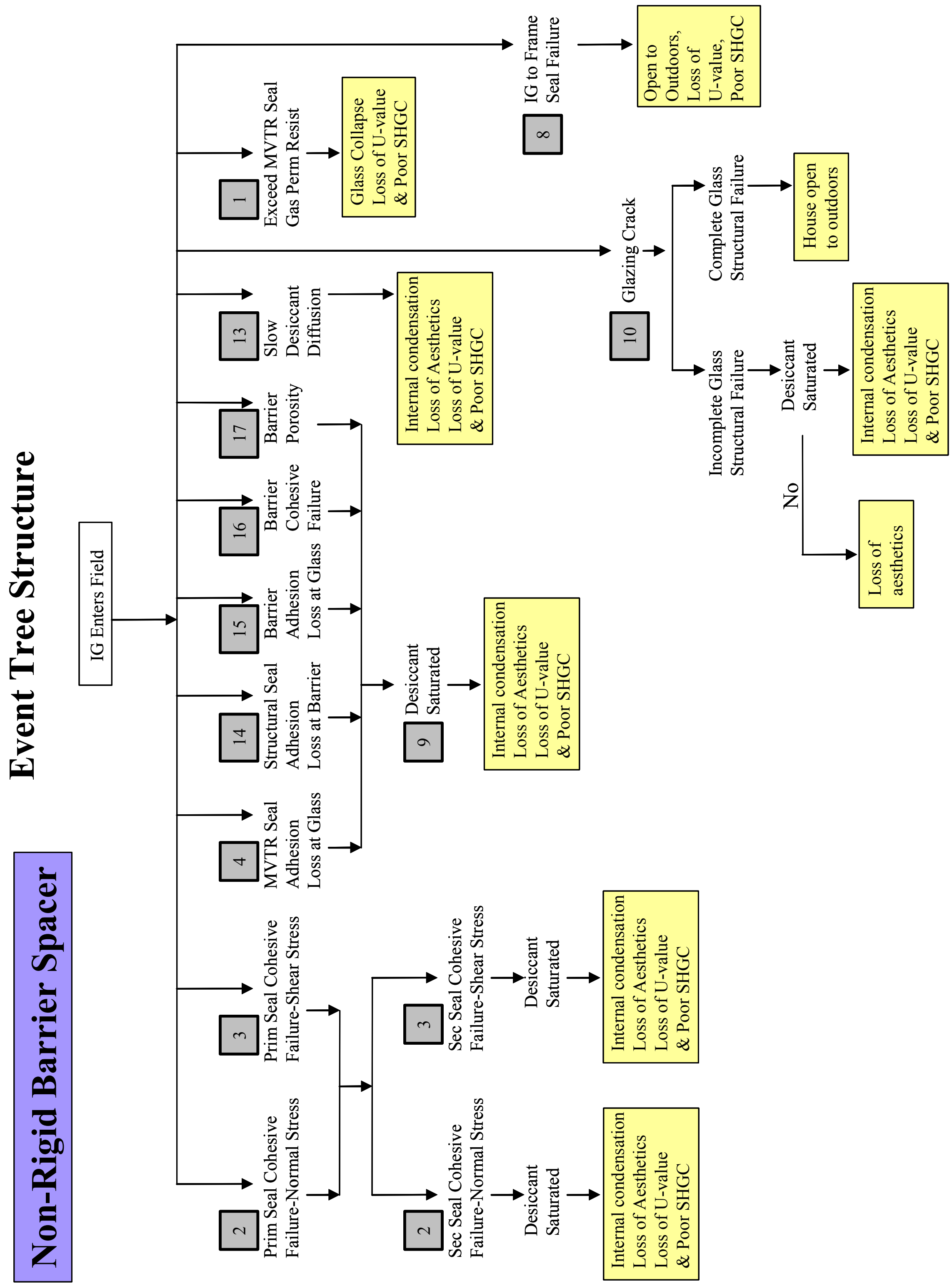


Figure 3-19. Sealant Gas Permeability Resistance Sub-Fault Tree

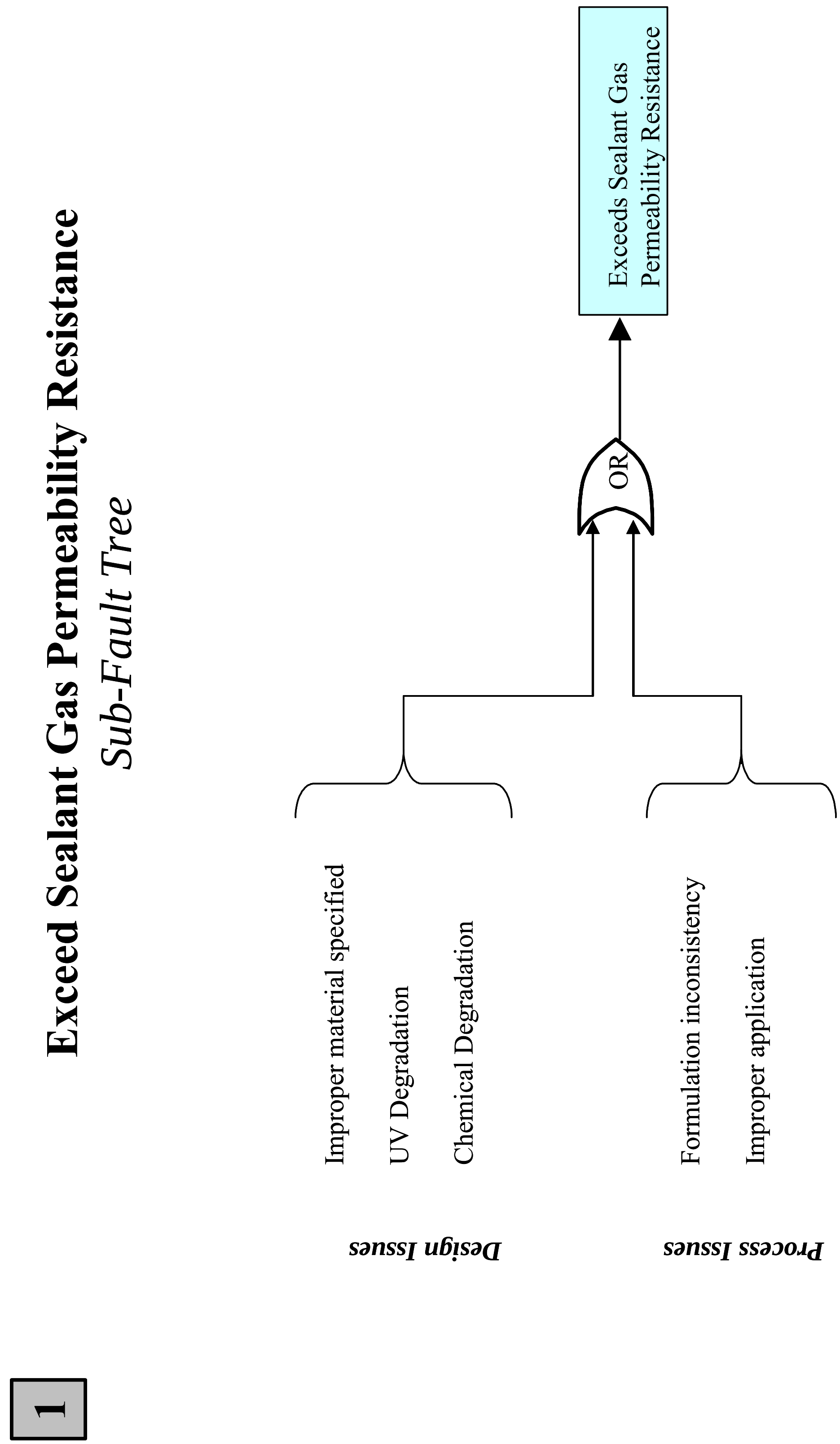


Figure 3-20. Sealant Cohesive Failure due to Normal Stress Sub-Fault Tree

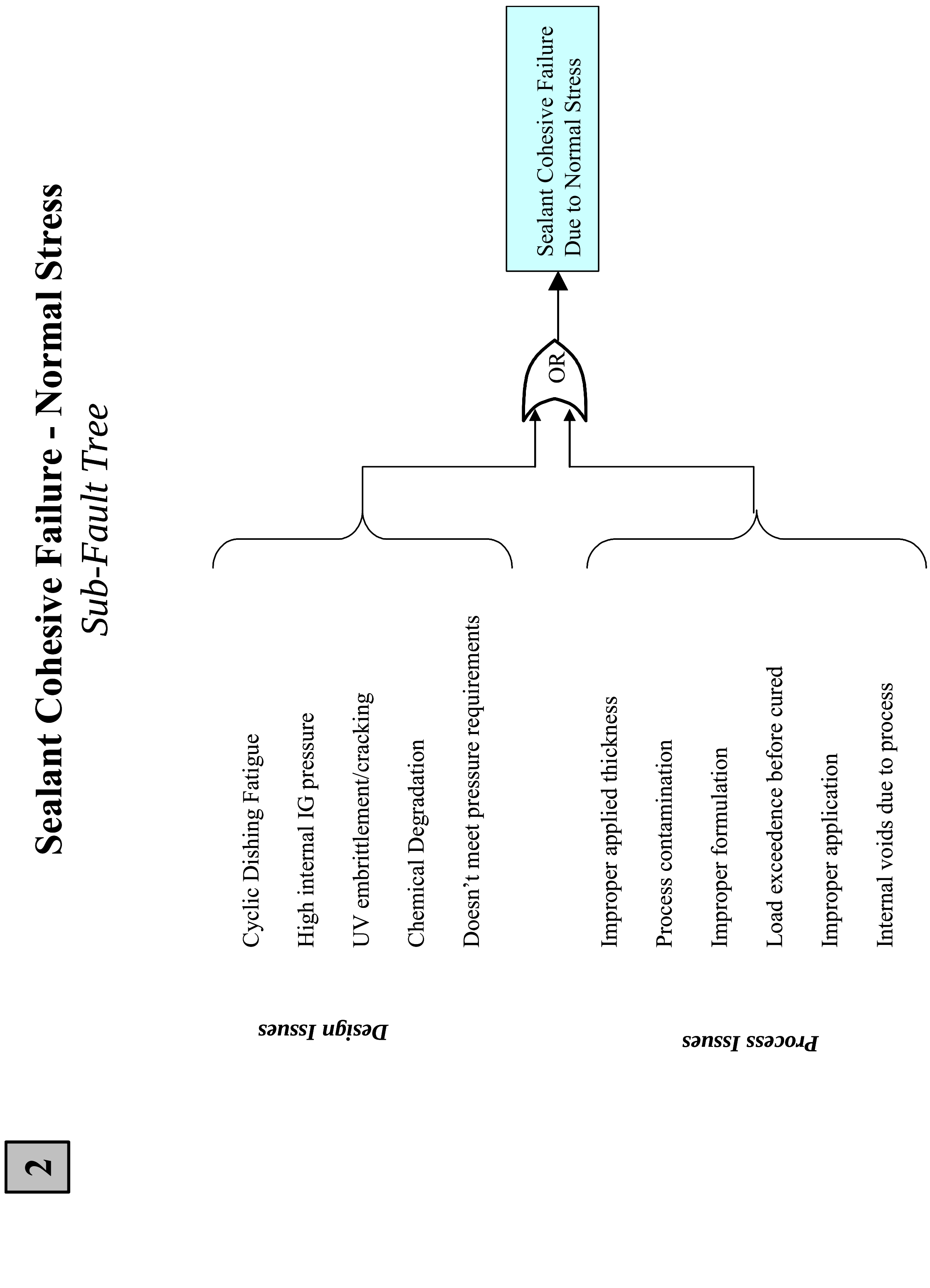


Figure 3-21. Sealant Cohesive Failure due to Shear Stress Sub-Fault Tree

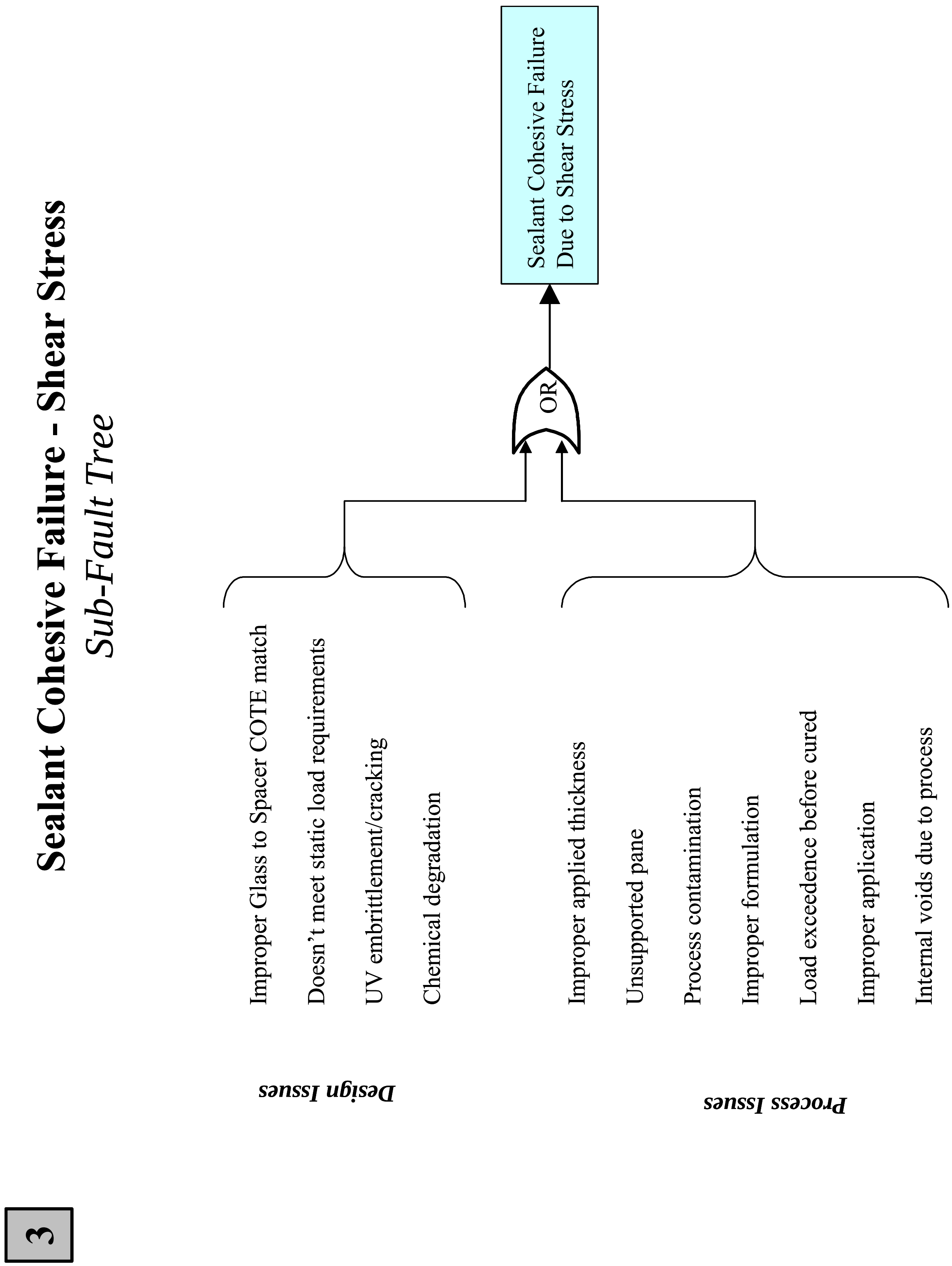


Figure 3-22. Sealant Adhesive Failure at Glass Sub-Fault Tree

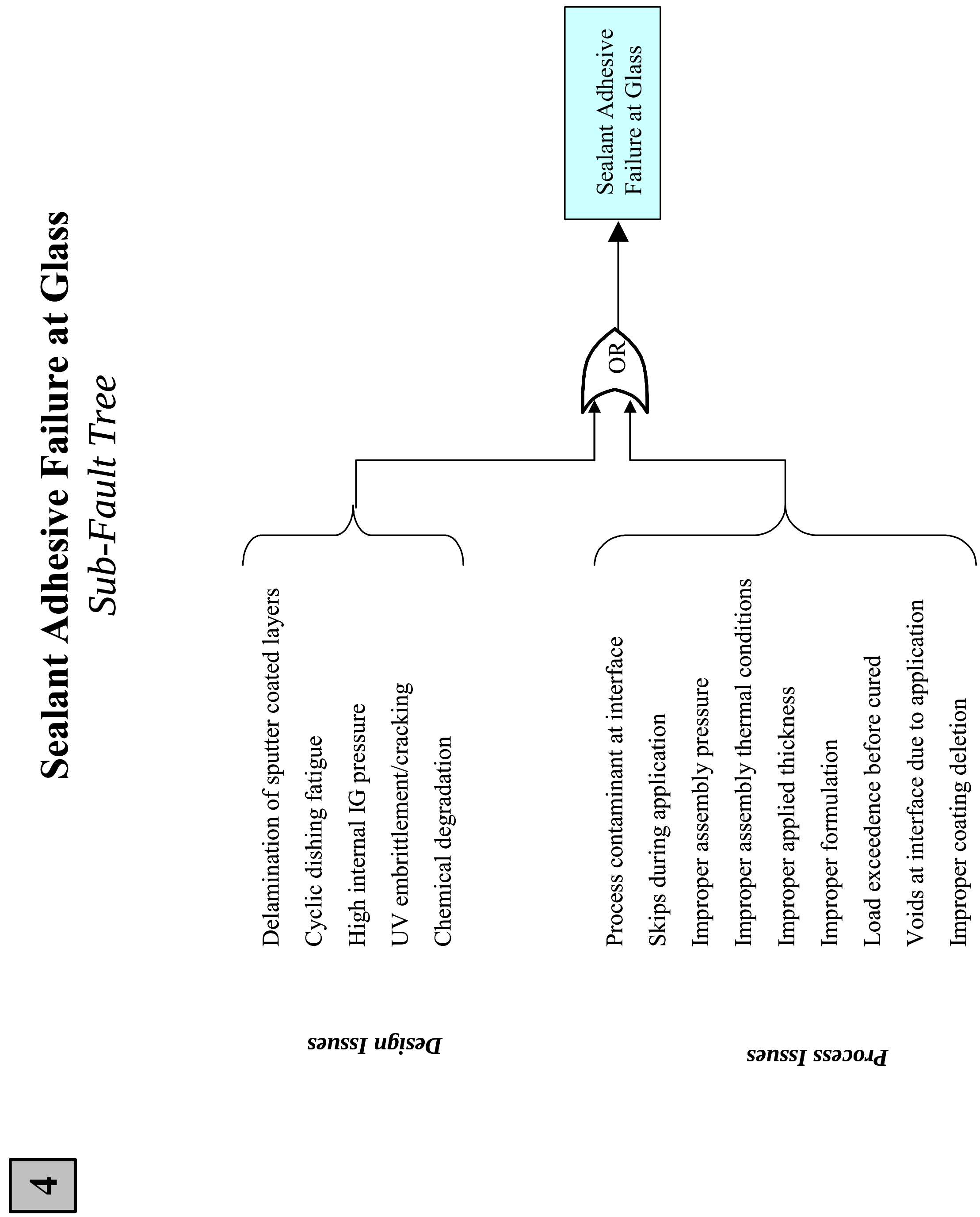


Figure 3-23. Sealant Adhesive Failure at Spacer Sub-Fault Tree

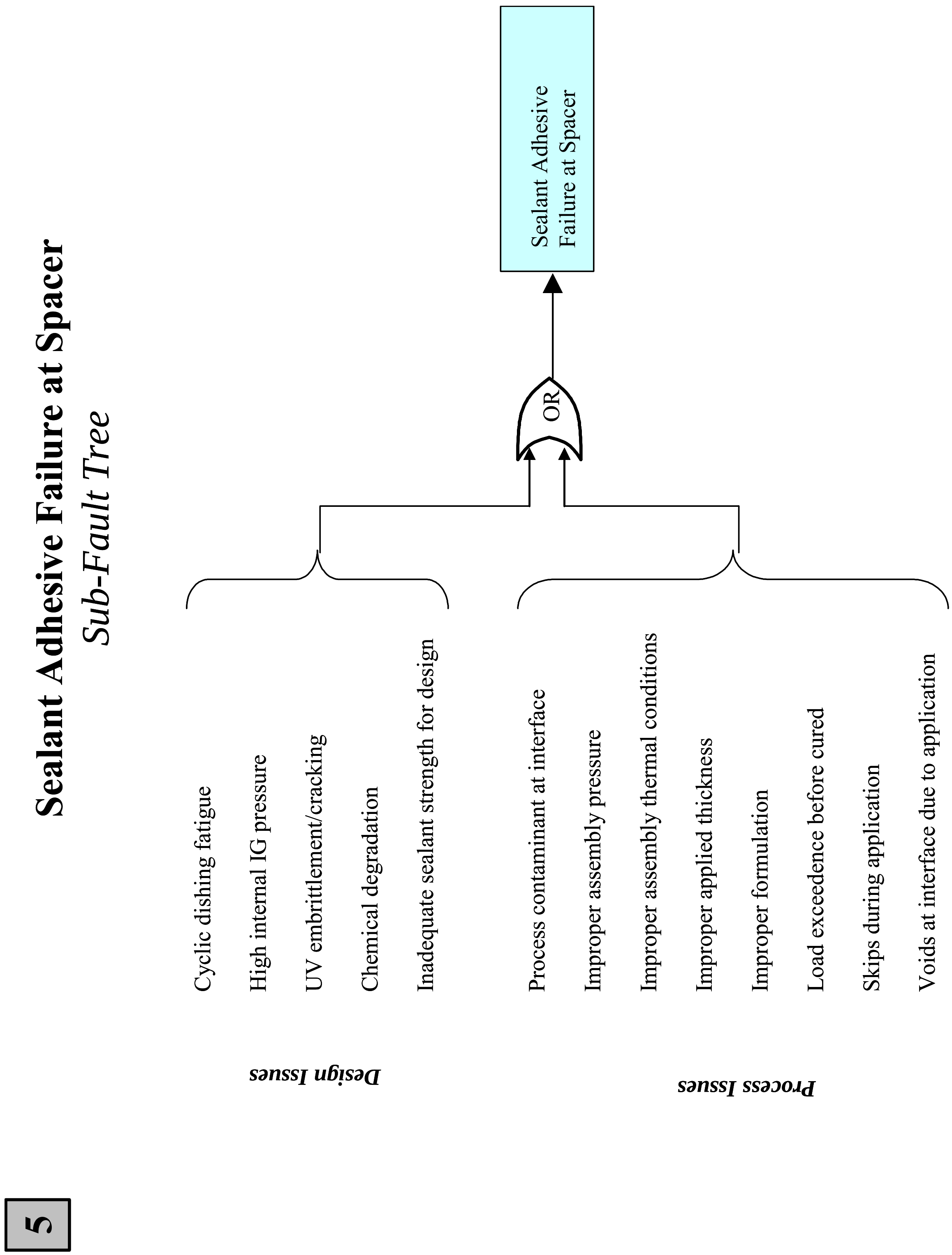


Figure 3-24. Inadequate Moisture Vapor Transmission Resistance Sub-Fault Tree

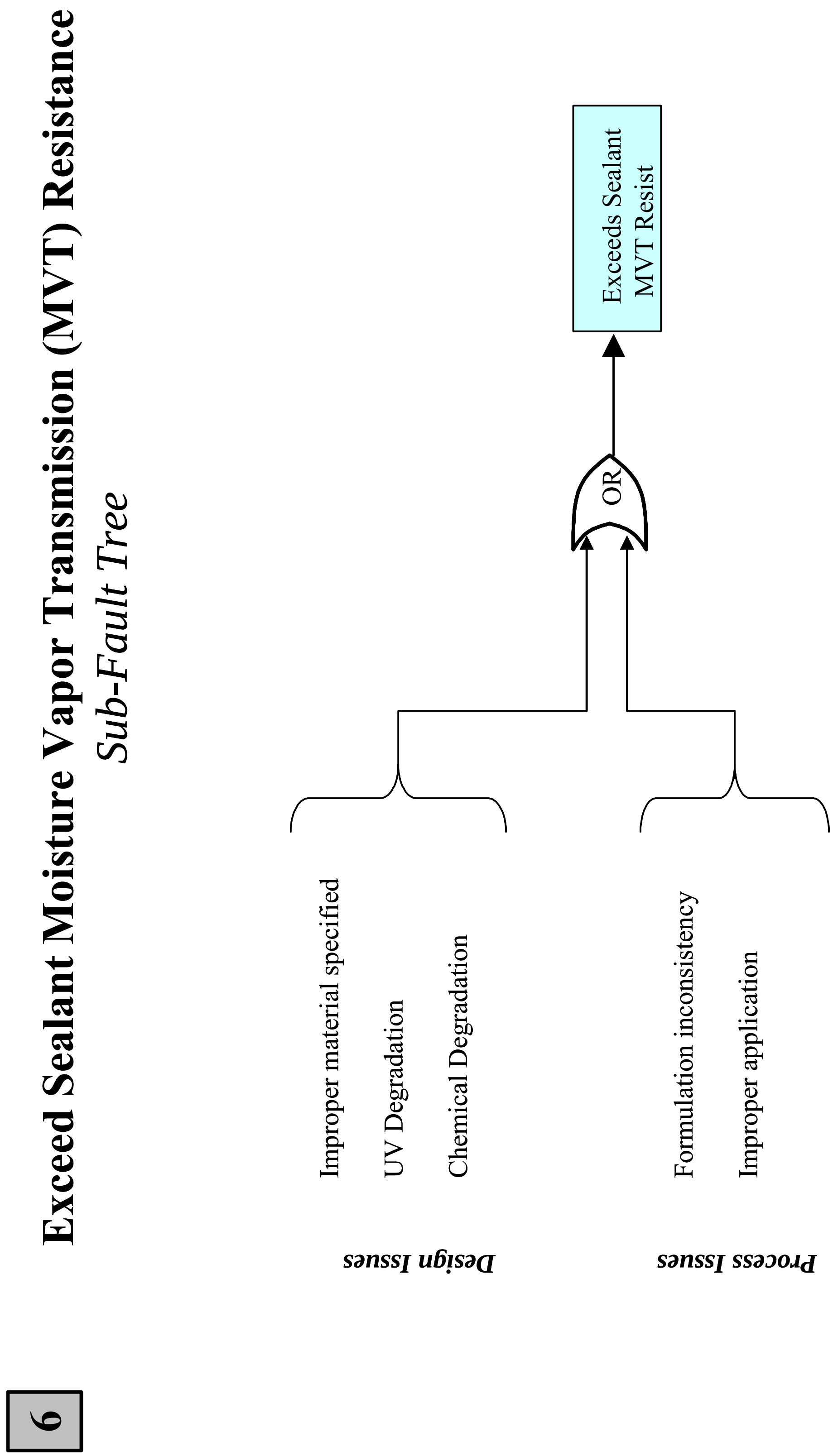


Figure 3-25. Loss of Spacer Barrier Sub-Fault Tree

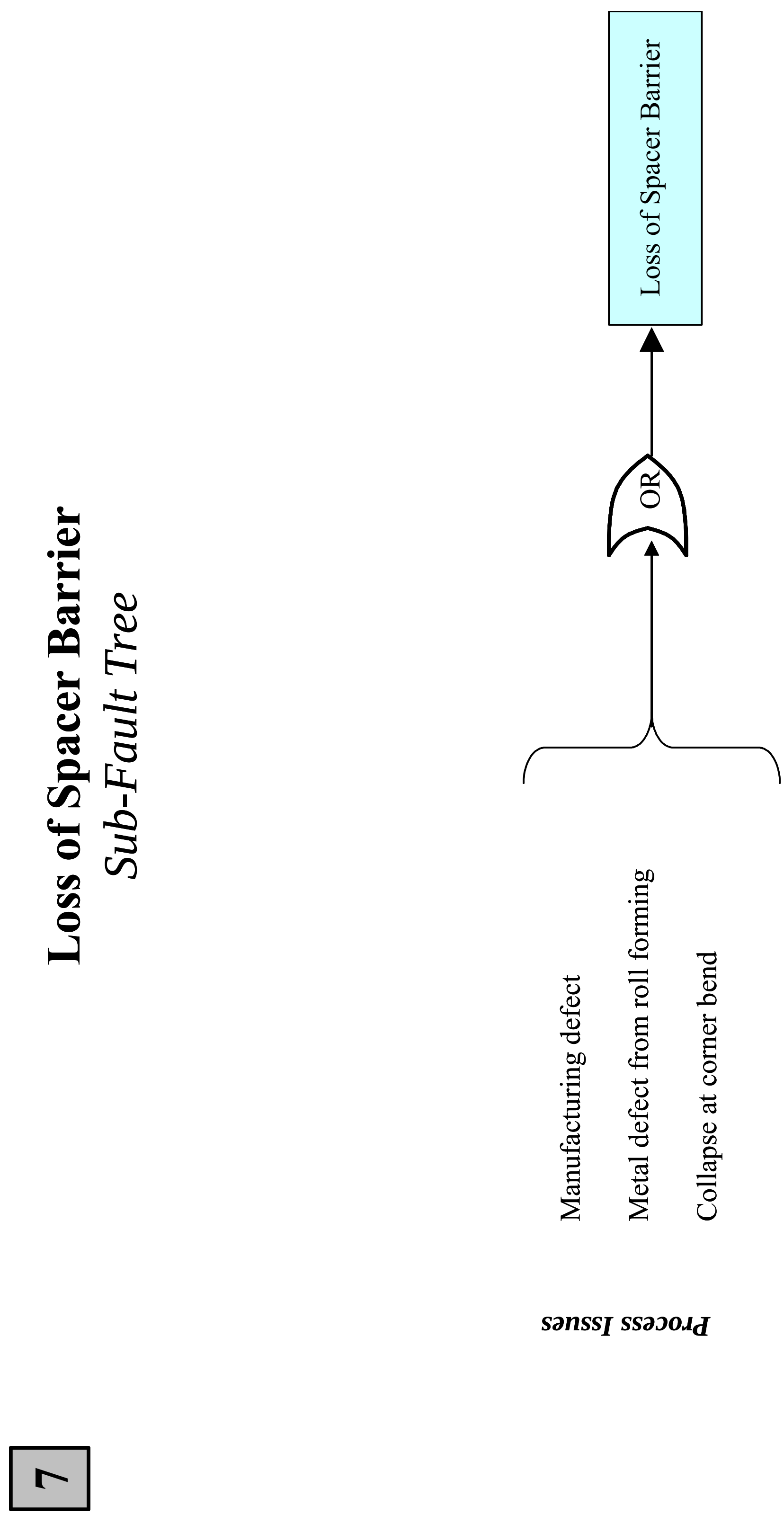


Figure 3-26. IG to Frame Seal Failure Sub-Fault Tree

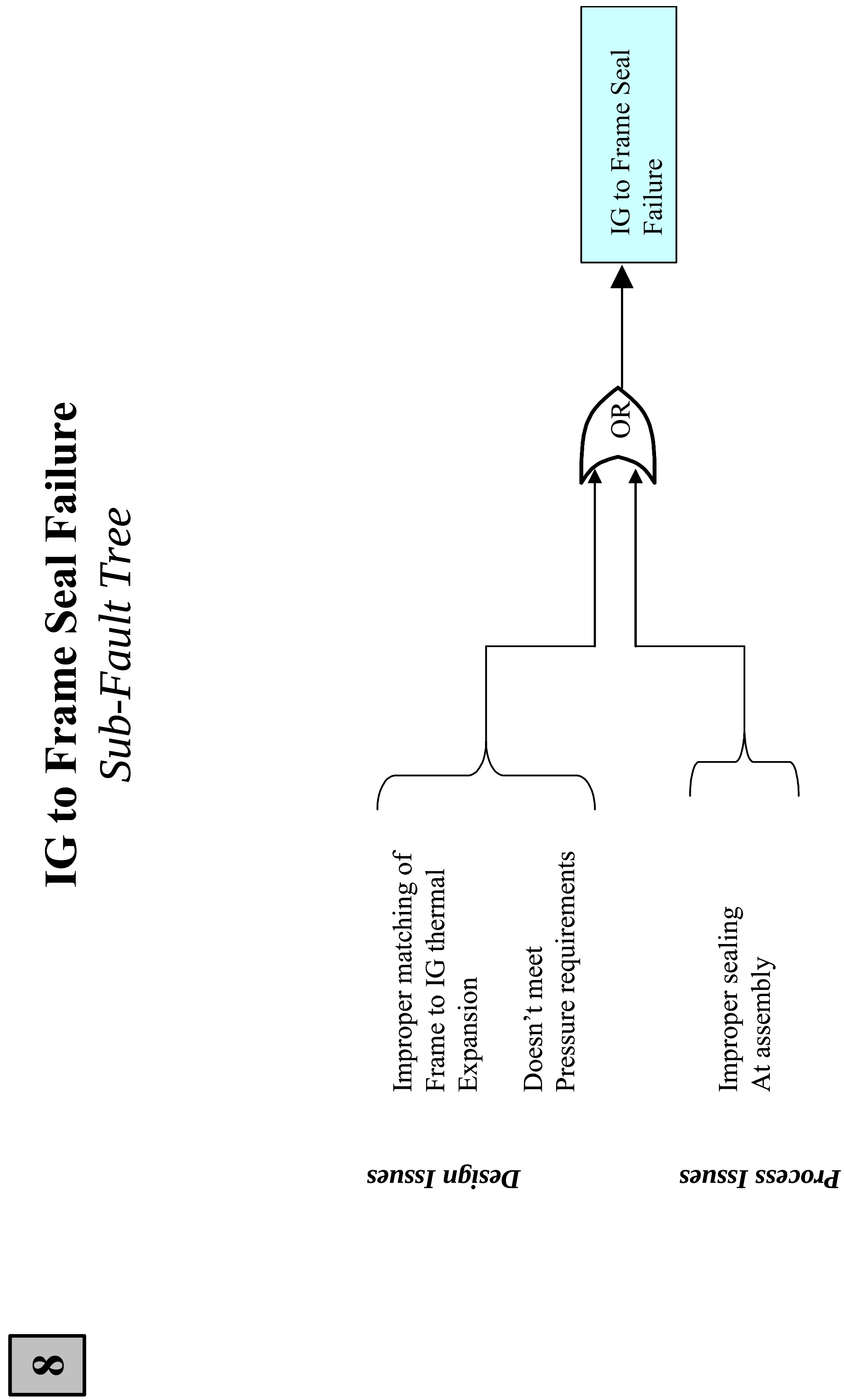


Figure 3-27. Desiccant Saturation Sub-Fault Tree

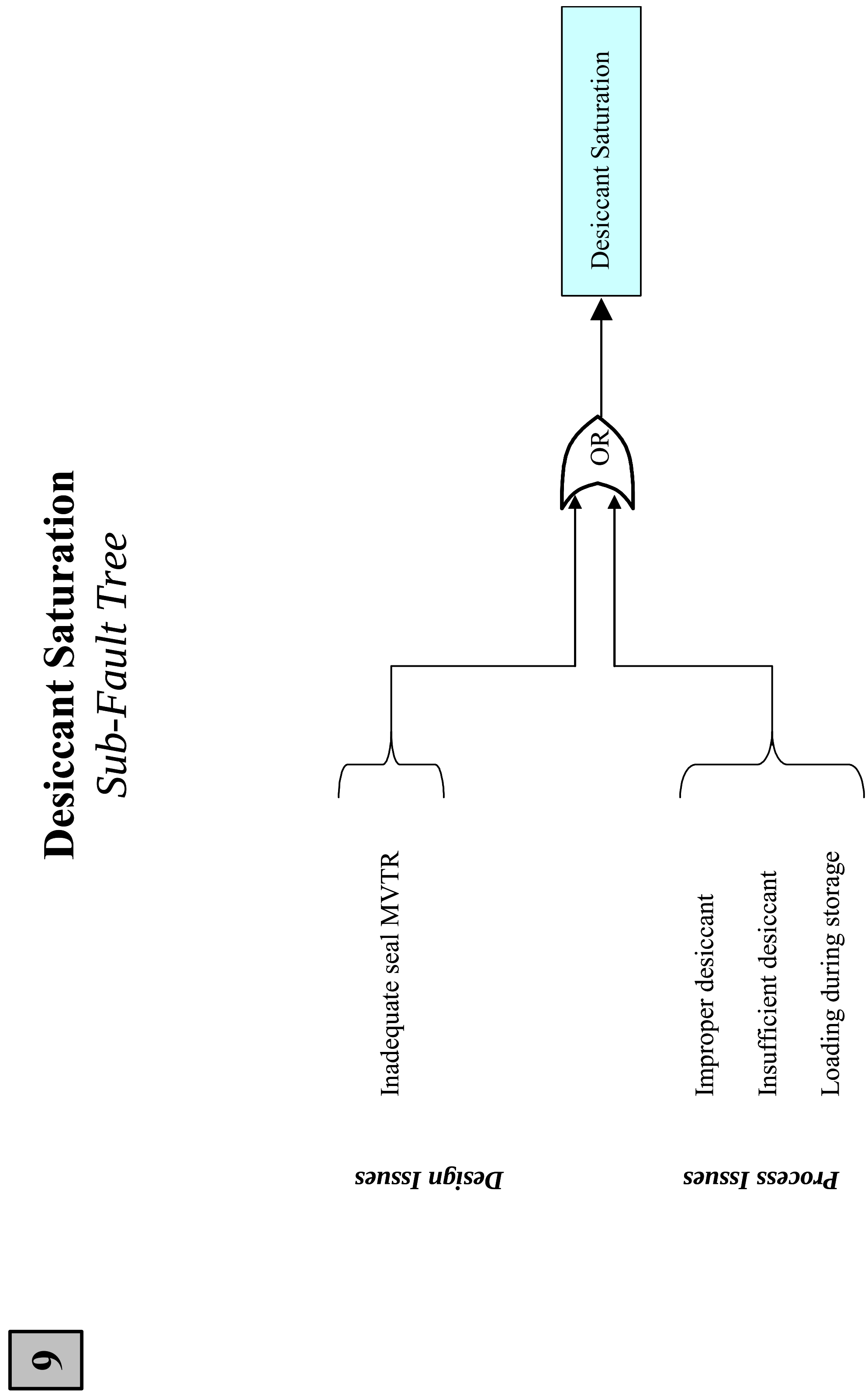


Figure 3-28. Glass Crack Sub-Fault Tree

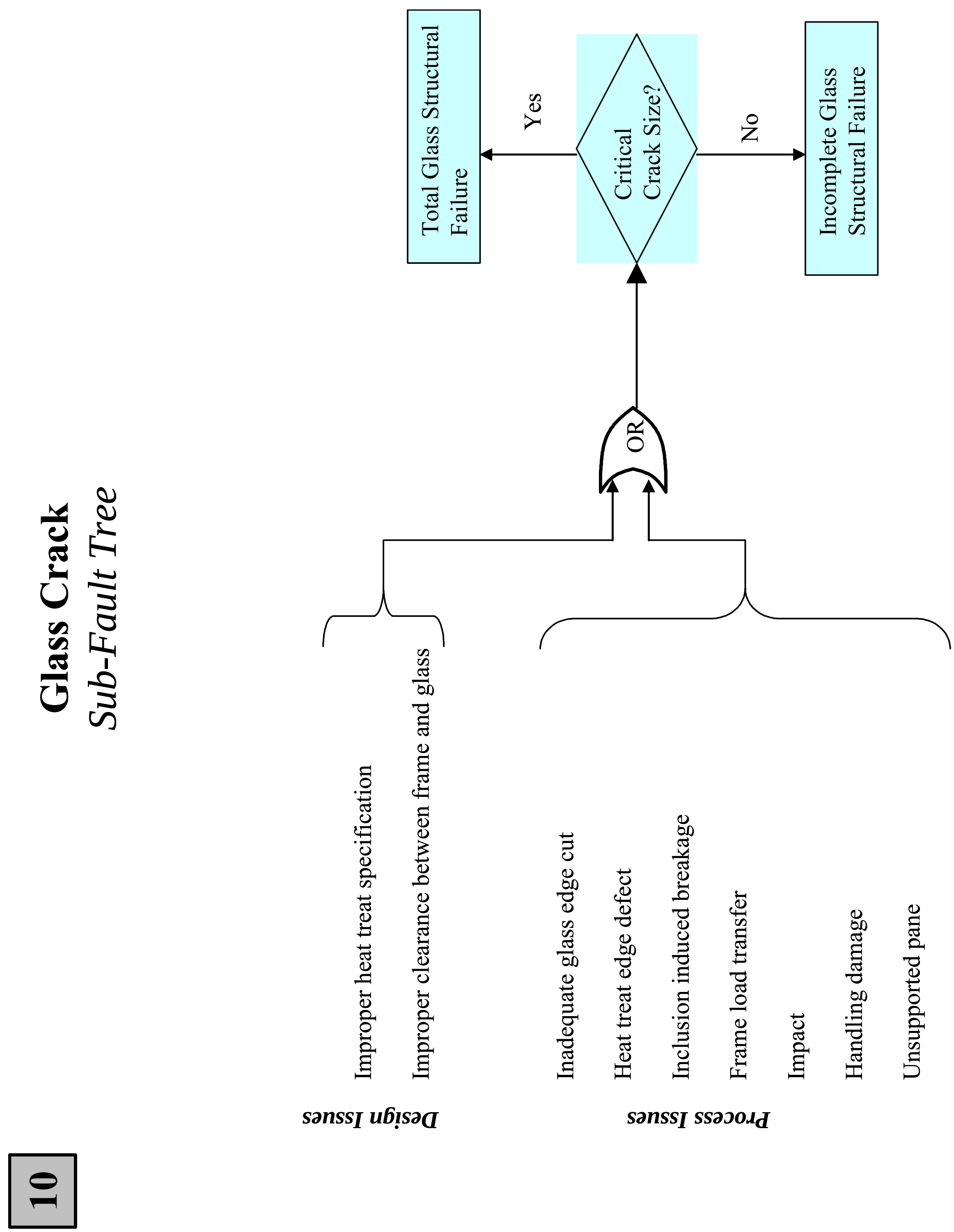


Figure 3-29. Loss of Spacer Barrier Sub-Fault Tree

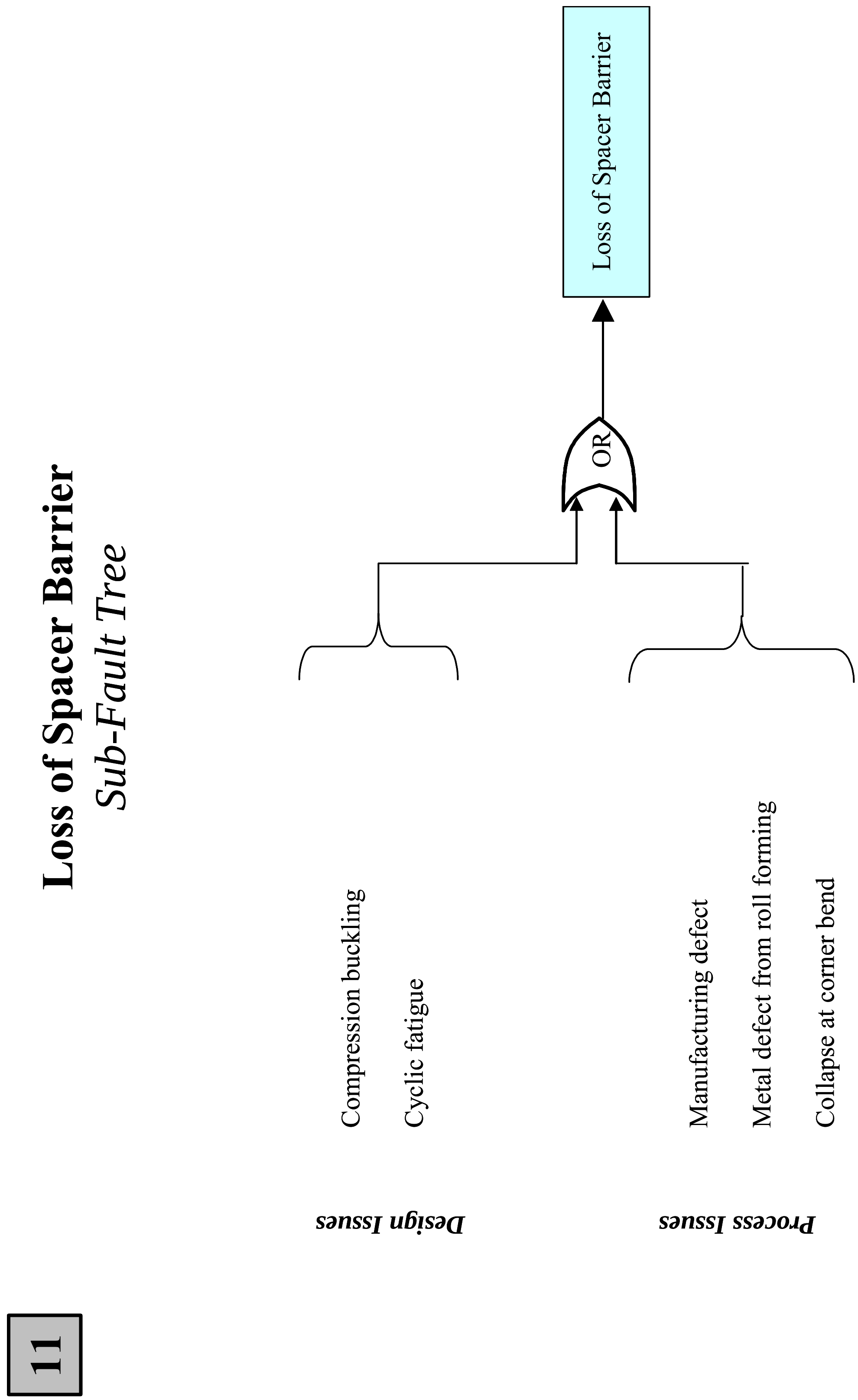


Figure 3-30. Desiccant Detaches Sub-Fault Tree

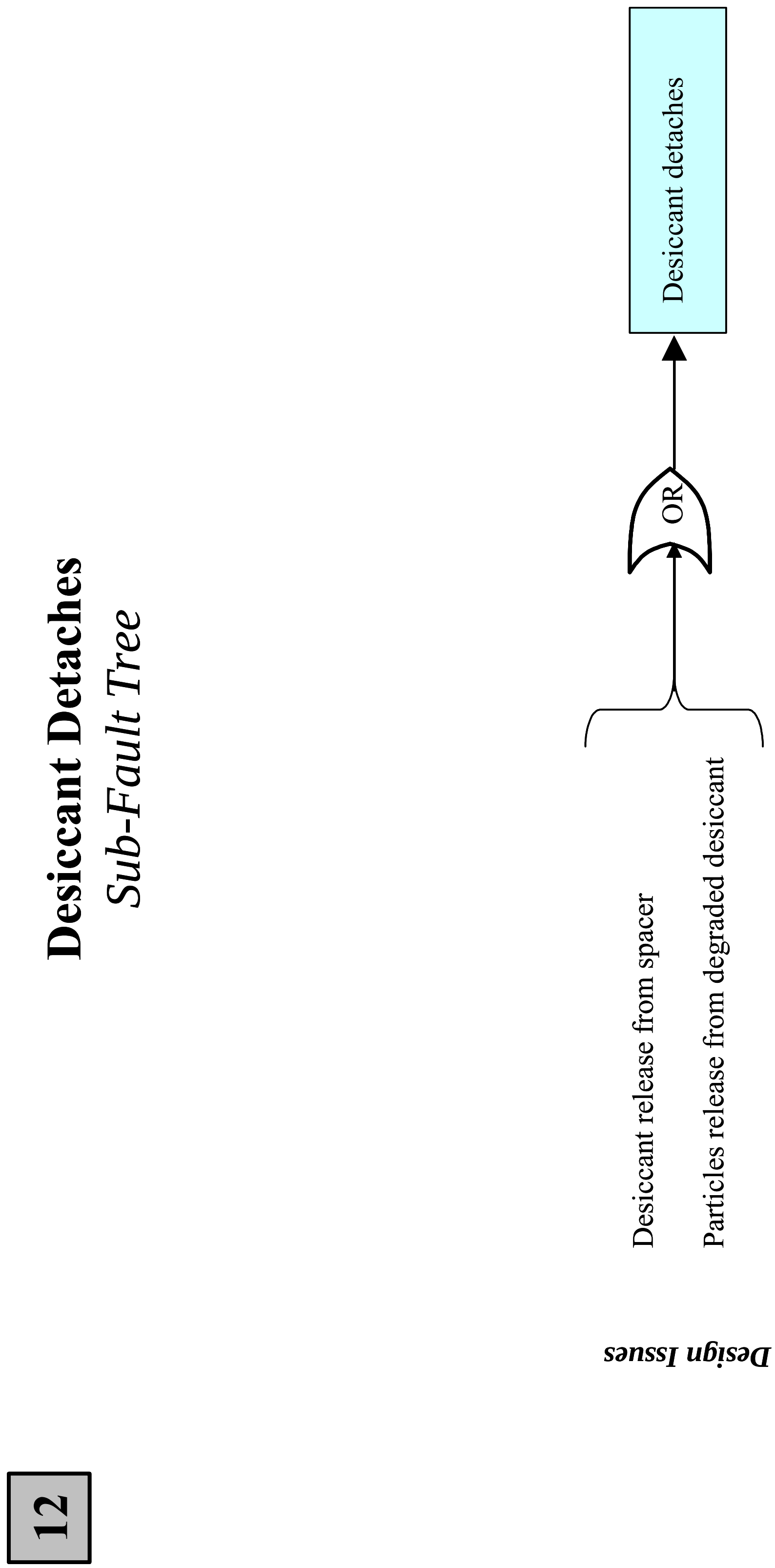


Figure 3-31. Slow Desiccant Diffusion Time Sub-Fault Tree

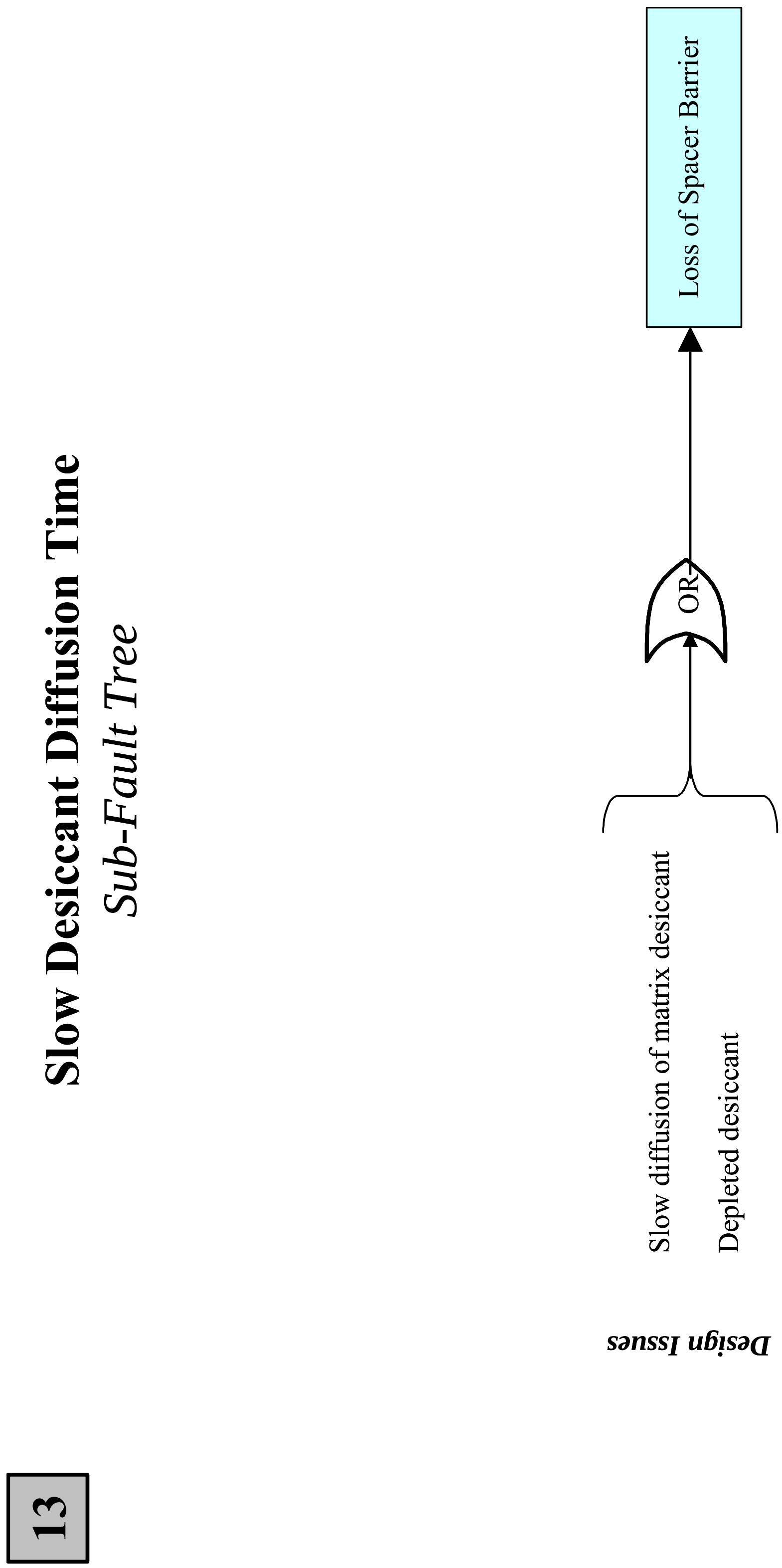


Figure 3-32. Structural Seal Adhesive Failure at Barrier Sub-Fault Tree

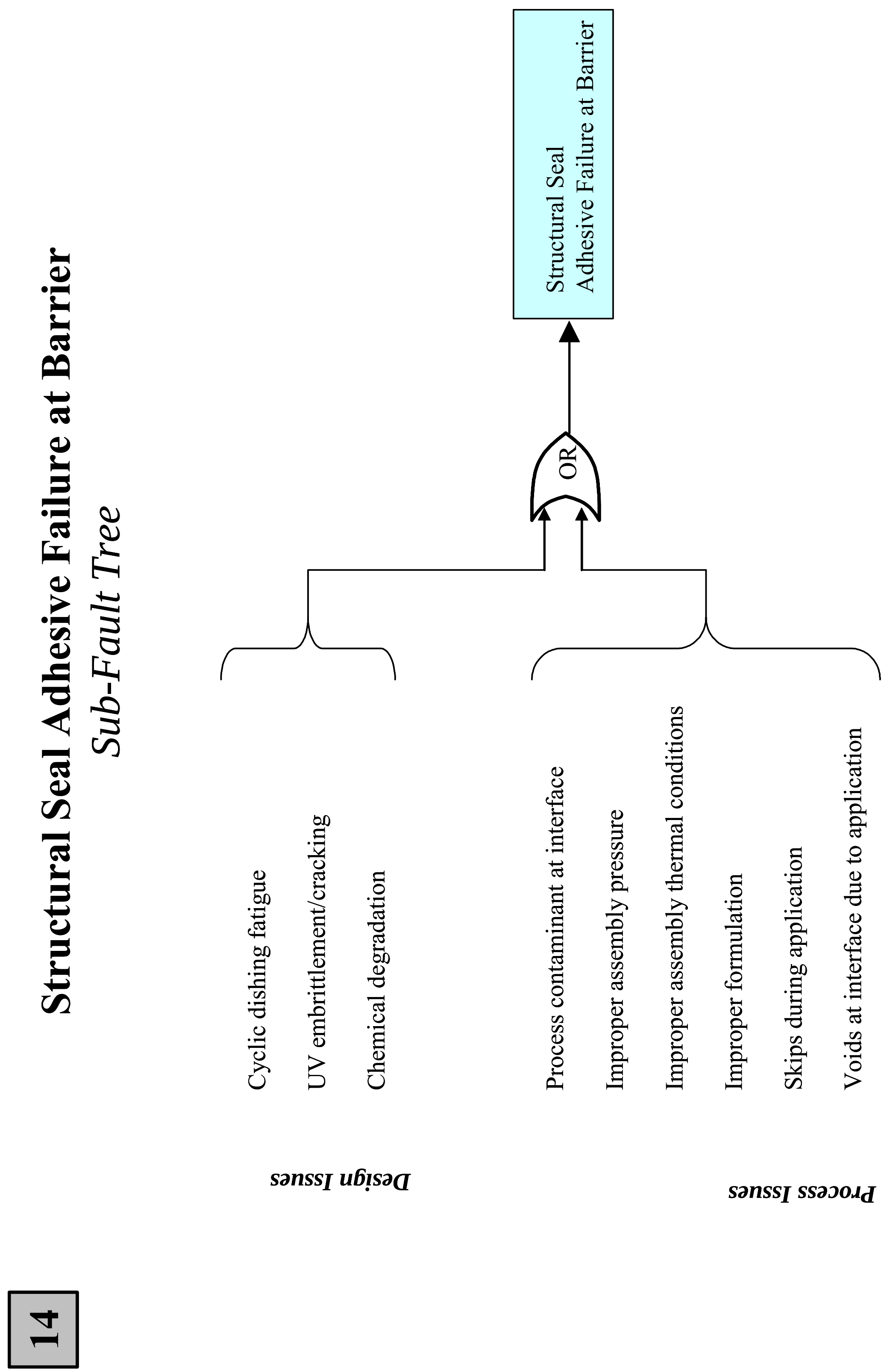


Figure 3-33. Barrier Adhesion Loss at Glass Sub-Fault Tree

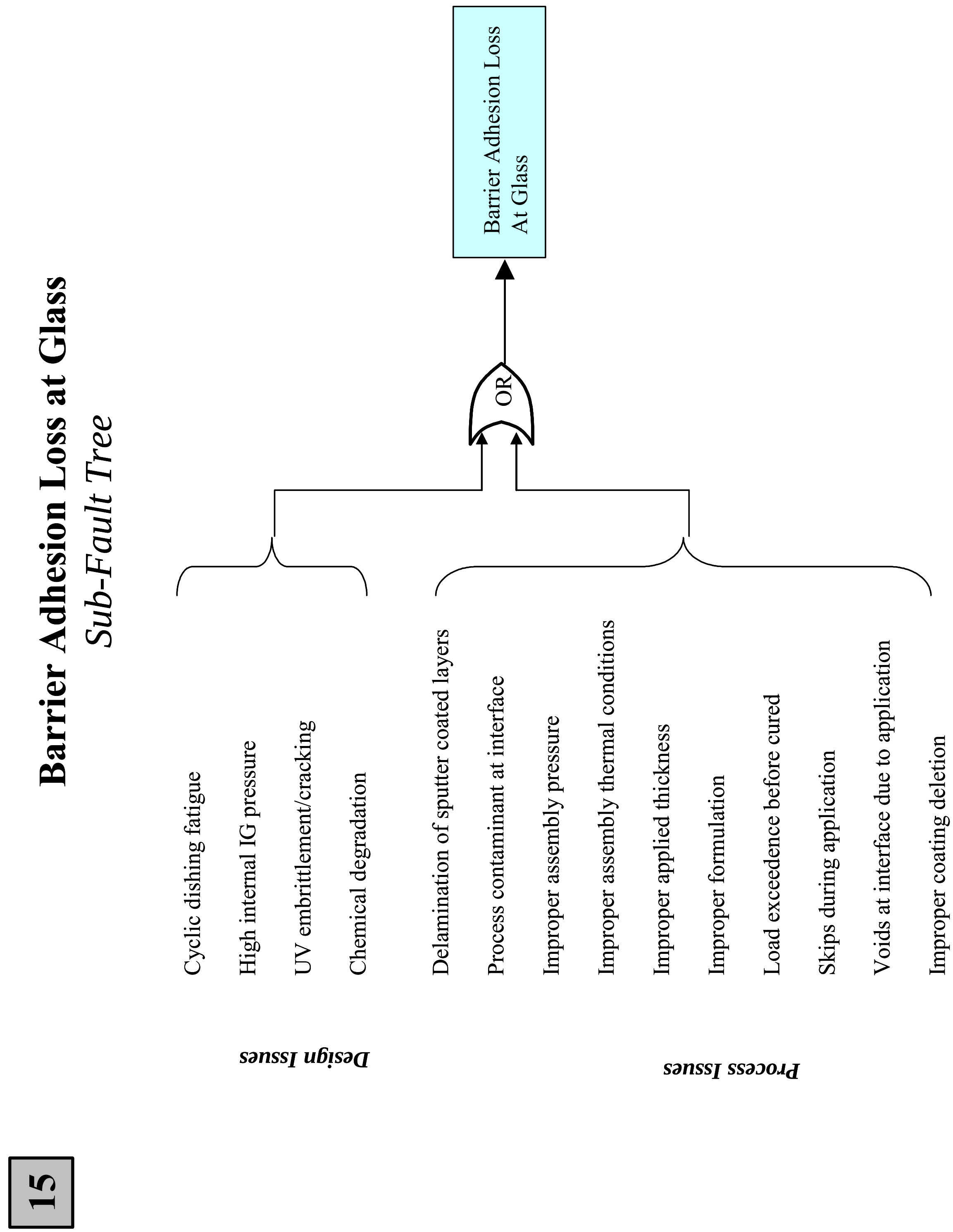


Figure 3-34. Barrier Cohesive Failure Sub-Fault Tree

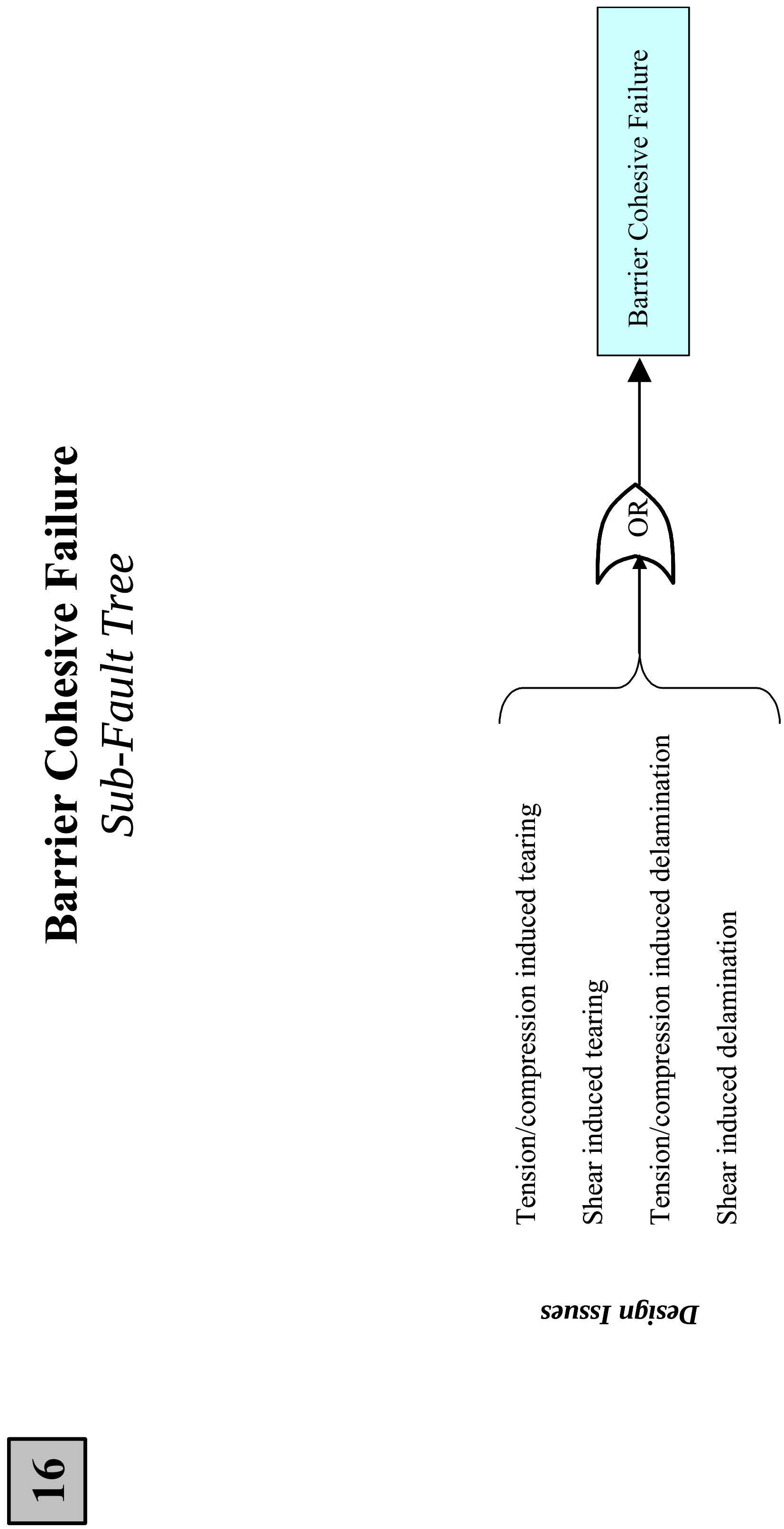
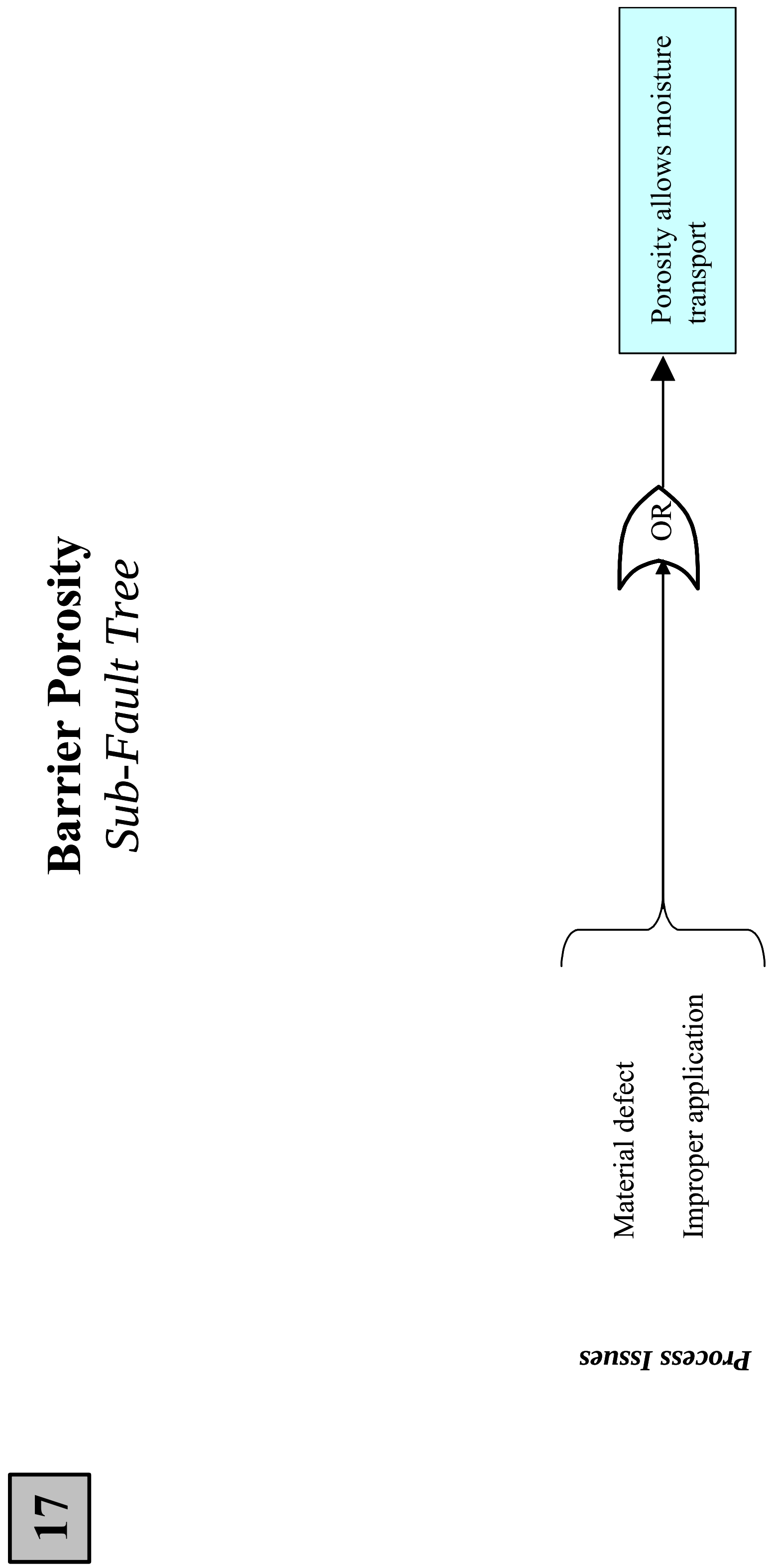


Figure 3-35. Barrier Porosity Sub-Fault Tree



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4. Technical Discussion of Failure Modes

Joshua Anderson, Tim Bender, Russell Pylkki, Douglas Wilken, Richard Hage

4.1 Overview of the Effects of Failure Modes

Insulating glass (IG) units are positioned as selective barriers between the external environment and buildings. Thermal and pressure loads will be exerted on the IG panes by the building itself. All environments will stress the IG with barometric pressure fluctuations, air temperature variations, wind loads, solar flux, and relative humidity. Some environments are even worse such as in coastal areas.

Given enough abuse, anything will fail eventually. When components of an IG experience enough degradation, they will experience failure.

Consumers notice the results of excessive degradation. The primary complaints regarding insulating glass units are internal water vapor condensation, external water vapor condensation ("frost rings" and water) and glass breakage of all kinds, in that order. Water condensation problems fundamentally occur because of sealant "failures".

The following four qualitative papers will discuss the various failures of the components of an IG unit:

- Normal Stress Cohesive Sealant Failure
- Shear Stress Cohesive Sealant Failure
- Sealant Adhesive Failure
- Glass Structural Failure

These papers will first identify the relevant environmental forcing functions. Then they will explain how these forcing functions couple to the IG unit. They will discuss the physical strength of the particular component in the insulating glass unit. Finally they will describe the actual failure event when the stress on the component exceeds its strength.

The final two papers will tersely introduce key secondarily-derived failures:

- Excessive Moisture Vapor Transmission Rate
- Net Gas Loss from the IG Air Space

The topics of these latter papers will be investigated more closely in Chapter 6.

4.2 Sealant Normal Stress Cohesive Failure

This document discusses the failure mechanism of normal stress cohesive failure within a sealant. Normal stress describes a stress state which involves either tension or compressive stress. This stress can be viewed as a distributed force applied perpendicularly, or normal, to the face of a cube, which tends to pull or push on the cube face. The complement of Normal stress is Shear stress, which is applied parallel to the face of a cube and tends to distort the cube due to twist.

Cohesive failure is defined as structural failure occurring anywhere within the bulk of the material. The complement of cohesive failure is adhesive failure, which does not occur within the bulk of the material, but occurs at the interface between the material and an adjoining material.

The moisture vapor transmission resistance (MVTR) seal for the varying spacer system design classes is defined as the seal whose primary purpose is to resist gas and moisture vapor transmission. The structural seal is defined as the seal which provides structural strength to the spacer system [1]. Although these principal functions are performed by each, there is also some overlap in that the MVTR seal provides some structural strength and the structural seal in some cases may contribute some resistance to gas and moisture vapor transmission.

The following sections will discuss this failure mode in the context of the overall competing stress – strength relationship. The environmental parameters which stress the system are discussed. The manner in which the environmental stress is translated to physical strength is then discussed. The resisting strength of the material is discussed in a manner consistent with the opposing physical stress. The failure event is then discussed in terms of how it is manifested.

Environmental Stress Quantification

The environment results in stress on the component due principally to pressure differential variations between the inside and outside of the IG. The pressure differential is primarily due to barometric pressure differential, differences of the internal and external temperature, and wind loading.

These temperature deltas will result in differential pressures due to the Ideal Gas response within the interior of the IG [2]. The relationship of the IG interior gas at state 1, its manufactured condition, and state 2, its operational condition is shown in equation 1.

$$\frac{P_2 \cdot V_2}{T_2} = \frac{P_1 \cdot V_1}{T_1} \qquad (1)$$

Complicating this analysis, however, is the fact that the IG balloons out to varying amounts as the interior becomes pressurized. This ballooning effect results in bowing of the glass panes, which in turn causes flexure at the spacer system, as the spacer system seeks to resist the bending moment. Different thickness of glass panes combined with different spacer systems and for different sizes of units, will result is differing amounts of ballooning and thus flexure. In general, however, the greater the resistance to ballooning, the more the internal pressure will increase for a given temperature increase. In addition to facilitating the ballooning, the internal pressure will induce bearing and shear along the periphery of the sealant.

Temperature within the IG and the environmental barometric pressure drive the flexure response. The variation in barometric pressure will be directly additive to the pressure differential across the IG exterior to interior. The temperature within the IG is developed due to thermal conduction, convection, and radiation effects. The conduction effects on temperature result from the temperature gradient between the environment and the interior of the dwelling. The convection effects are due to the heat transfer of flowing air on the outside of the IG and natural convection within the IG. The radiation contribution is due to the radiation transfer of solar energy to the interior IG space. This is a function of effective window absorptivities, which are driven by coatings.

Variation in relative humidity will affect the cohesive response of the sealant in that the resulting variation in exposed moisture can result in variations in modulus of the sealant [3]. Exposure to UV can affect behavior by limiting the strength and ductility of the sealant [4].

Environmental to Physical Stress Translation

The sealants can experience normal stress due to either an imposed bending moment or due to pure applied tension or compression, as shown in Figures 4-1, 4-2, and 4-3. As can be seen pure normal tension and normal compression result in stress fields with uniform stress magnitude. The stress field imposed by a bending moment is more complex, however, as peak tensile and compressive stress occur at the edges of the cross section. Across the section the stress assumes a profile which spans the two extremes.

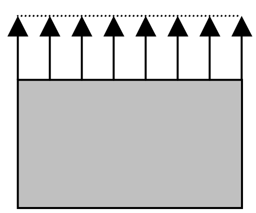

Fig.4-1 Normal Tension

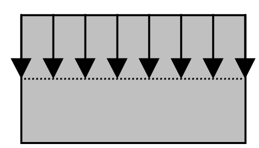

Fig. 4-2 Normal Compression

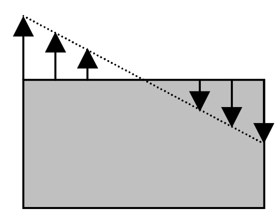

Fig. 4-3 Bending Moment

The spacer system thus experiences a bending moment due to the flexure of the glass pane and sees normal stress due to both the plate wanting to push out of the IG and from the internal pressurized gas pressing on the interior of the spacer. These stress states can lead to either ultimate strength failure or cyclic failure depending on the magnitude of the loading cycles.

The magnitudes of the stress for each case depend on the amount of the force or moment to be resisted. The stresses seen in each sealant also depend on the configuration of the spacer system. The relative modulus of the sealants, their cross sectional areas and their thicknesses all define how the stress field is distributed between the sealants. An additional complicating factor is the effect of the spacer on the stress distribution. The spacer contributes to compression resistance and in some case to tension and moment resistance.

First the case of uniform tension and compression loading will be considered. For the purposes of the following discussion the MVTR sealant will be referred to as the primary sealant (as it is the primary MVTR seal). The structural sealant will be referred to as the secondary sealant. In considering how the force and thus stress is distributed between the sealants, the system should be viewed as effective springs as shown in Figure 4-4.

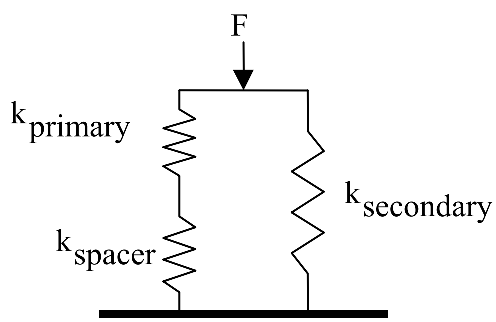

Fig. 4-4. Spacer system elements as effective springs.

The effective spring stiffness for each element can be developed by considering the normal stress, Modulus, cross-sectional areas, and stress as shown in equations 2 and 3:

$$\sigma = E \cdot \varepsilon \qquad (2)$$

$$\frac{F}{A} = E \cdot \left[\frac{\Delta t}{t} \right] \qquad (3)$$

Therefore, the effective spring stiffness for each element can be expressed as:

$$k = \frac{F}{\Delta t} = \frac{E \cdot A}{t} \qquad (4)$$

Two design classes which would require special cases of the above representation are the TPS system and the corrugated metal spacer system. The TPS system does not contain a rigid spacer, all of the structural force resistance is provided by the sealants [5]. The above model would be modified to account for this case by eliminating the spring stiffness of a spacer. Another special case would be the corrugated metal spacer [6]. In this case, the metal spacer is in parallel with two sealant elements, and it would thus be modeled as such a parallel spring. Because it is significantly more rigid than the sealants, it would resist the majority of the compressive load. The corrugated spacer would not resist tensile load; however, as it is not properly attached to the glass to withstand tensile load. To account for this the corrugated spacer would thus be modeled as a parallel spring with its high stiffness for the compression case, but with zero stiffness for the tension case.

With respect to the generic design case shown in Figure 4-4 significant insight can be gained into the loading response of the system. It is useful to consider the ratio of the forces which are withstood by each of the elements. To consider this it is necessary to model the parallel-series spring system. By performing this analysis, it is clear that the primary seal and spacer each withstand the same force, and their combined effective stiffness determines the magnitude of this force. The effective stiffness of the primary sealant and spacer in parallel is described as:

$$k_{spacer\,\&\,primary} = \frac{k_{primary} \cdot k_{spacer}}{k_{primary} + k_{spacer}} \qquad (5)$$

The ratio of the force, with respect to the total force, which is absorbed by the spacer and primary seal, is as follows:

$$\frac{F_{spacer\,\&\,primary}}{F} = \frac{k_{primary} \cdot k_{spacer}}{k_{primary} \cdot k_{spacer} + k_{primary} \cdot k_{\sec ondary} + k_{spacer} \cdot k_{\sec ondary}} \quad (6)$$

The ratio of force absorbed by the secondary sealant is as follows:

$$\frac{F_{\sec ondary}}{F} = \frac{k_{primary} \cdot k_{\sec ondary} + k_{spacer} \cdot k_{\sec ondary}}{k_{primary} \cdot k_{spacer} + k_{primary} \cdot k_{\sec ondary} + k_{spacer} \cdot k_{\sec ondary}} \quad (7)$$

In general, it can thus be seen that the more stiff the spacer and primary (MVTR) sealant effective spring is, the more load they will carry. The effective stiffness is governed by their combined stiffness. Since it is the more compliant member, the primary sealant will drive the load it and the spacer see. The individual stiffness is proportional to the modulus and cross sectional area and is inversely proportional to the thickness. Thus the higher the modulus, the greater the cross sectional area, and the thinner it is, the greater the primary sealant's stiffness and the more load it will see. Since the stress is the force distributed over the area, the area factor will not come into play if the stress is considered rather than the force. With respect to stress it can still be seen that higher modulus and thinner thickness will result in higher stresses.

The response to a bending moment is more complicated than simple tension and compression loading. It is more complicated because the stress distribution as it responds to a bending moment is a function of the compressive and elastic moduli within the material and it is also dependent on the configuration of the sealants and the spacer. With consideration to differences in moduli, the linear relationship shown in Figure 4-3 holds, with the maximum compressive and tensile stress being equal and opposite. If the moduli differ, the slopes and maximum of the compressive and tensile distributions will differ. The neutral axis of the distribution will move from the geometric center as well. It is important to note that for elastomeric sealants, the modulus can be a significant function of temperature. Properties vary substantially with temperature. The moduli also can vary significantly with relative humidity; however, as the cross linking density is effected by the moisture [3]. The moduli is directly related to the cross linking density.

The response to flexure is further complicated by the use of a rigid spacer. The corners of the spacer will in many cases function as a pivot point for the bending moment response. It will particularly function as a pivot point in a dual seal box spacer system if the primary sealant is reasonably thin with respect to the secondary sealant. For the corrugated spacer, the spacer edges will act as pivot points as well. The pivot point which is driven by these configuration relationships will drive the bending resistance stress field.

Although the stress field is more complicated, the effective spring relationships defined previously are useful to understand the relative nature of the stress distribution. The spring stiffnesses must be used in concert with the effective moment arms of sealants with respect to each other and the spacer pivot point in order to make statements regarding the resistance to the bending moment.

It is useful to think of the sealants in terms of their elastic modulus and resulting spring stiffness, however, it is also necessary to consider non-elastic response of the materials. In particular, it is necessary to consider creep, stress relaxation, and damping. A material is said to experience creep when it stretches over time due to a constant applied force. This behavior is a plastic, permanent deformation strain, in contrast to the elastic response represented by modulus. Stress relaxation is a behavior common to many elastomeric materials. It is seen as material retreating back to its prestrained configuration. It occurs due to the material seeking equilibrium nearing its unprocessed state. Damping is due to internal friction loss of a material. These internal energy dissipations result in, for instance, beam oscillations tending to decay, rather than oscillate indefinitely. It is clear that each of the considerations are relevant to sealant response. Two approaches are typically taken to capture these issues [7]. They are the Maxwell model, and the Kelvin-Voigt model, shown below. In each case it is seen that the spring model of a sealant is complicated by including a dashpot which dissipates energy as a function of strain rate. The Maxwell is useful for modeling stress relaxation. The Voigt-Kelvin model is useful for modeling creep and damping.

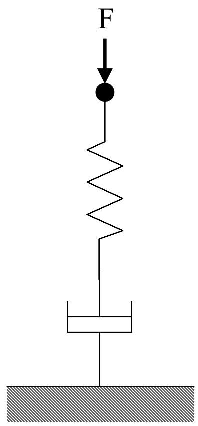

Fig. 4-5. Maxwell model

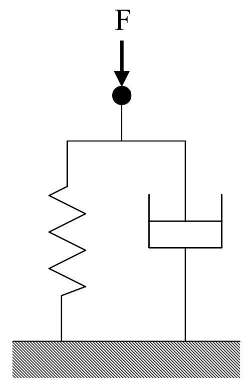

Fig. 4-6. Voigt-Kelvin model

Finally, there is often a complex stress field on the sealant. Normal stress coupled with shear stress, coupled with bearing stress from the interior of the IG often are simultaneously pressing on the sealant material. The shear and multi-axis stress fields can add with the normal stress to cause an effective normal stress failure. The two planes of normal stress can be combined with the shear stress to determine the maximum normal principal stress defined equation 8 [8]. This maximum stress can then be compared with the yield or allowable strength of the material to determine if failure will occur.

$$\sigma_{\max,\min} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x + \sigma_y}{2}\right)^2 + \tau_{xy}} \qquad (8)$$

Physical Strength

With respect to cohesive stress, the relevant strength parameters are the ultimate strength and the yield strength. These values are generally available for the initial condition of sealants. However, these strength values can degrade due to interaction with the environment. Environmental factors of UV, temperature, humidity, and precipitation can significantly alter properties of improperly specified sealants. The yield strength of sealant materials have been shown to be highly dependent on their service temperature [7]. The yield strength has also been shown to be highly strain rate dependent [7]. Thus the rate of temperature, UV, or pressure loading will impact the ability of the sealant to resist the stresses. Sealant embrittlement and cracking can occur if the formulation has insufficient robustness to the environment. Sealants often lose ductility at lower temperatures, making them more susceptible to brittle fracture [7]. If insufficient additives are present, the photons of UV radiation may degrade the sealant bonds sufficiently to cause embrittlement [7]. Exposure to unfriendly chemicals during its operation may also lead to cohesive failure [9]. Properties can degrade over time during field exposure, but in the production environment, the properties also vary as well. Rather than degrading, after application sealants take a significant amount of time to properly cure [10]. As they are curing, their properties are typically increasing to approach their properties expected for field performance. While curing it is imperative that their pre-cured ultimate strength is not exceeded.

Finally it is important to note that the definition of cohesive failure depends on the IG effect which is of concern. The definition can be stated in terms of the size of failure path which results in failure. A failure path which is a pin hole through the width of the sealant may result in vapor passing and thus internal condensation. A failure path which covers the full cross sectional area of a sealant results in complete structural failure. The discussions of fatigue and ultimate strength excedence are applicable for considering both these cases with respect to the defined failure dimensions. Also as mentioned previously, if interior voids or flaws are present, the ultimate strength failure can be initiated more readily or cyclic fatigue failure can be accelerated.

The Failure Event

What level of structural cohesive damage results in failure is dependent on what failure effect is being considered. A cohesive failure which progresses to loss of continuous material throughout an entire cross section would meet the traditional definition of a complete structural failure. A cohesive failure which progresses to a continuous pin hole across the length of a cross section would meet the requirements for allowing gas and vapor to pass through a material. This would result in an internal condensation failure, for example.

The IG will see normal and flexural cohesive stress as a result of the IG interacting with the environment. This interaction will result in sealant loadings which are seen as normal stress distributions. In many cases the stress distributions will be uniformly distributed tension or compression stress fields superimposed with flexural response bending moment stress fields. These stress fields will either lead to sudden cohesive failure or will lead to fatigue failure.

Sudden cohesive failure results if there is an excedence of the ultimate strength of the material. If a design is developed to properly account for expected environmental loading, this failure can only occur due to unexpected excedence of environmental stresses, improper fabrication, out of spec material properties, or internal flaws as a result of the production process. If excessive environmental stress is the cause, the design requirements should be reevaluated to assess whether the design exhibits a sufficient safety factor in its intended region. A particularly important factor in fabrication is thickness of sealant. As was seen from the stiffness models, the proper thickness of the adhesive is critical to achieving the anticipated stress levels. If the thickness is too thin, the result will be higher adhesive stresses. Out of spec material properties could be the cause if the modulus is out of spec or if the ultimate strength is out of spec. Of course out of spec ultimate strength is a problem if it is sufficiently low that it does not exceed the stress imposed by its intended environment. Out of spec modulus could potentially be a problem if it is either too low or too high, depending on the design. If it is too low a greater amount of the force will be resisted by the other sealant. The other sealant may then experience loads greater than intended by the design. If it is too low it will also have more deflection which could lead to maximum strain excedence.

Internal flaws from the production process can lead to ultimate strength excedence because they introduce two complicating problems: they reduce the sealant's area to resist the force, and they introduce internal stress concentration regions. The reduction in sealant area can lead to failure as the stress resulting from a force is inversely proportional to amount of area available to resist the force. The magnitude of stress concentrations caused by internal flaws are related to the sharpness of the voids. The sharper the edges or tighter the radii of the flaws, the greater the amount of stress concentration. Stress concentration is a significant concern, as it could easily result in the nominal stress being increased several times. The types of flaws which could be present are dependent on formulation and processing issues. An insufficiently clean vendor formulation process may result in a variety of contamination that could be experienced as macroscopic flaws. Cleanliness and consistency must be used in the formulation process to avoid such problems. If a good formulation has been received from a vendor, contamination may occur in the production facility as the IG spacers are fabricated. Again cleanliness and process consistency are necessary to avoid introduction of such flaws.

Fatigue, of course, is the gradual failure of a system due to a cyclic load. The material sees damage as peaks of cycles reach sufficient levels of stress. The damage is sufficient to degrade the material, but is not initially high enough to cause ultimate strength failure. The damage can be observed as either loss of effective cross sectional area or as degradation of material properties [7]. Loss of cross sectional area occurs when cracks propagate through a material, growing with each sufficiently high cyclic stress. Degradation of material property can occur for instance by polymers loosing cross linking bonds as sufficiently high levels of alternating stress are applied. There are two models which are useful when considering fatigue failures: the Goodman diagram and fracture mechanics. The Goodman diagram is more of a macro level model and the fracture mechanics deals with the stress field in more detail.

Fracture mechanics is a more physics based approach to explain crack growth. Although it is used often to quantify crack growth in homogeneous solids, it has been used to model crack growth in some sealant materials [7]. If the material is understood to the proper resolution, however, the same principles may be applicable to sealant materials. Fracture mechanics theory is typically used by considering the rate of crack propagation as a function of an element termed the stress intensity factor. The stress intensity factor is represented by the symbol K. It is a means for expressing the forcing function of crack growth. Stress intensity factors have been developed for a variety of loading and crack propagation conditions. For crack growth, it is typically the range of stress intensity over a cycle which is viewed as the driving function in crack growth. The range over a cycle is represented as below.

$$\Delta K = K_{\max} - K_{\min}\Big|_{cycle} \qquad (9)$$

The cyclic stress intensity factor range is used to predict the crack growth rate by using the following relationship, which is termed the Paris crack growth equation. As can be seen from the equation, the crack growth rate is related to the stress intensity factor through the empirical constants c and b. The constants are generally a function of the material.

$$\frac{da}{dN} = c \cdot [\Delta K]^{b} \qquad (10)$$

It should also be noted that the stress intensity factor range is not constant during crack growth. It is a function of crack depth and loading stresses, both of which change during propagation. Therefore, although the parameters of the Paris crack growth equation are constant for a given loading situation and material, the crack growth rate is not.

$$\Delta K = f(\text{material, geometry, crack depth, residual stresses, loading stresses}) \qquad (11)$$

Once the Paris equation parameters are obtained for a material and the stress intensity factor has been modeled as a function of crack depth, the crack growth can be integrated either directly or numerically [11]. The result of the integration is the crack depth as a function of number of cycles, as is shown in Equation 12.

$$a_N = \int_0^N c \cdot [\Delta K]^b \, dN + a_0 \qquad (12)$$

The stress intensity factor is also a function of the type of loading. It is necessary to understand the type of loading in order to correctly apply fracture mechanics theory. A simple representation of the loading case of normal stress induced crack growth is shown in Figure 4-7.

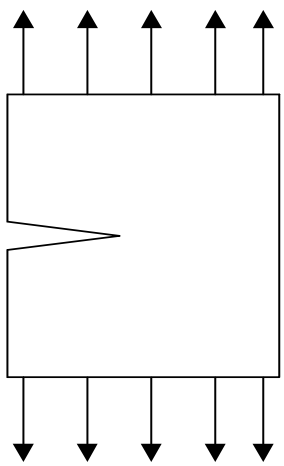

Fig. 4-7. Fracture Mechanics Loading Condition for Normal Stress loading

The Goodman diagram [12] is shown in Figure 4-8. The Goodman diagram provides a criterion for determining what is an acceptable contribution of mean and alternating stress for a material. The parameters on the diagram are defined as follows:

$$\sigma_{mean} = \frac{[\sigma_{\max} + \sigma_{\min}]}{2} = \text{mean stress} \qquad (13)$$

$$\sigma_{alternating} = \frac{[\sigma_{\max} - \sigma_{\min}]}{2} = \text{alternating stress} \qquad (14)$$

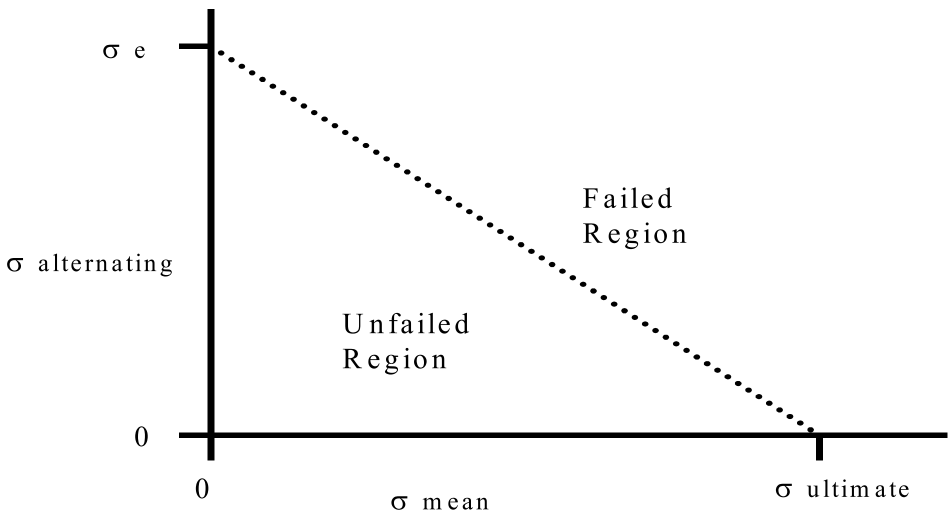

Fig. 4-8. Goodman Diagram

This approach is useful when the stress on the object can be expressed as a cyclic stress with a maximum and minimum value for each cycle. The mean and alternating stress for each cycle is calculated from the maximum and minimum stresses of each cycle. The failure criteria for purely alternating stress is the endurance limit stress, σ e. The failure criteria for purely static stress is the ultimate stress, σ ultimate. The Goodman criteria states that failure will occur if the plotted combination of mean and alternating stress is in the stated region above the straight line between endurance limit and ultimate strength. This approach has been historically shown to provide reasonable fit to reality when structures fail due to fatigue failure where fatigue happens progressively rather than suddenly.

This approach will be useful for describing fatigue failures of IG components if the following criteria are met:

- Component stress over the warrantable lifetime can be expressed as an equivalent cyclic stress superimposed over a static stress
- Endurance limit stress for a component is defined as no failure during its warrantable lifetime
- Component endurance limit can be measured experimentally
- Component ultimate strength can be measured experimentally
- Failure occurs due to fatigue

To be useful for the current project, the endurance limit, mean stress, and alternating stress will all have to be expressed as a function of the design and the environmental region. The ultimate strength will be a function of the object's material, which will not be dependent on design or geometry. The material properties in the design will also drive the stress translation. The mean stress must be a function of design and region because the stress translations are design specific and the equivalent maximum and minimum environmental stress, which results in the mean stress, is temperature and thus region specific. The alternating stress must be a function of design because the stress translations are design geometry and material dependent. The alternating stress must also be a function of the environmental region because both the amplitude and the frequency of the alternating environmental temperature oscillations are dependent on the environmental region. Finally, the endurance limit strength is both design and environment dependent. It is design dependent because the design material and geometries define the stress translation. It is environment dependent because, if the endurance limit is defined as the level of alternating stress which does not cause failure during the object's useful life, the number of oscillations expected during the useful life must be quantified. This number of oscillations will be dependent on the environmental region considered; thus it must be tied to a specific environmental region. It is necessary to define the time duration since sealant materials and non-ferrous materials in general, usually do not have an endurance limit for which an infinite number of cycles can be achieved, as is the case for ferrous materials [7].

The mean and alternating stress may be expressed in terms of the region's temperature range and the modulus of the material, with empirical constants to include the design geometrical effects. The modulus of the material will in general be included because it is a direct translation from the strains to the physical stresses. Since for temperature excursions the environment drives the strains, the modulus will be important to the environment to physical stress translations. It is also possible that the geometric effects can be captured in terms of lengths, cross sections and inertias, if sufficient model development is performed.

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4.3 Sealant Shear Stress Cohesive Failure

This paper discusses sealants failing cohesively due to shear stress. Shear stress can be viewed as a distributed force applied parallel to the face of a cube. It tends to distort a cubical element into a rhomboid. The complement of Shear stress is Normal stress, which is applied perpendicular to the face of a cube and tends to compress or stretch.

Cohesive failure is defined as structural failure occurring anywhere within the bulk of a material. The complement of cohesive failure is adhesive failure, which does not occur within the bulk of a material, but at the interfaces between materials. The level of structural cohesive damage resulting in failure is dependent on the failure effect being considered (i.e. structural failure or internal condensation).

This paper will discuss the failure mode in the overall context of the competing stress-strength relationship. Specifically, how environmental stress manifests itself as physical stress on the sealant, as well as the strength of the sealant to resist that stress and its eventual failure event.

Environmental Stress Quantification

Shear stress experienced by the sealant is primarily caused by environmental temperature variation. The mechanisms involved are differential thermal expansion of the two materials joined by the sealant and pressurization/depressurization of the airspace between the lites of glass [1]. Temperature not only affects the materials and the environment surrounding the sealant, it also affects the sealant itself. Specifically, a sealant's ability to stretch, conform and absorb stress is reduced by lower temperatures.

Internal IG pressurization is described by the ideal gas pressure law: PV=nRT [2]. The P-V volume relationship is related to the variation in temperature within the IG interior. The function relating the IG interior temperature to its environmental conditions is beyond the scope of this paper, but would need to include the following terms: indoor & outdoor temperature, indoor & outdoor airspeed, barometric pressure, glass thicknesses, glass coatings, spacer width, and spacer material. This pressure differential results in shear loading of the sealant with respect to the glazing, as increased internal pressure tends to push the spacer system out of the IG.

UV contributes inasmuch as it leads to detrimental effects on the sealant response properties [3]. Similarly humidity and precipitation can degrade a sealant's mechanical response by reducing its moduli.[4].

Environmental to Physical Stress Translation

Shear is most easily represented as shown below. It is a force acting parallel to an object's edge. Shear stress is related to the shear force by normalizing the shear force to the area of the shear face. The result of the shear stress is a distortion of the object. The amount of distortion can be represented by the distortion angle, ϕ. Newton's law requires that each force must be reacted by an equivalent resistant force in an element. The reaction force that results from a shear load is seen as an equal shear force on the complementing face and acts in the opposite angular direction. The shear stress is represented as τ.

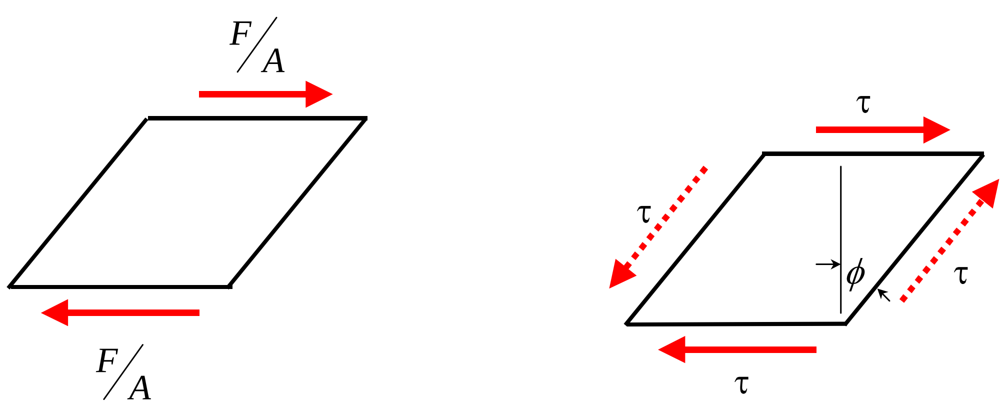

Figure 4-9. Shear stress

The shear stress relationship to the distortion angle is analogous to the relationship between normal stress and normal strain. As Young's Modulus is used to represent normal stress as a function of linear strain, the Shear Modulus is used to represent the shear stress as a function of the angular strain. The relationships are as shown in Equations 1 and 2:

Shear Stress: $\tau = G \cdot \phi$ (1) Normal Stress: $\sigma = E \cdot \varepsilon$ (2)

Not only are the Shear and Normal stress relationships analogous, the Shear Modulus and the Young's Modulus can be related directly by the following relationship.

$$G = \frac{E}{2 \cdot [1 + \upsilon]}, \qquad \text{where: } \nu = \text{Poisson's ratio} \qquad (3)$$

Shear stress is developed in IG units through three generic mechanisms:

- bulk relative movement of two substrates,
- differential thermal expansion motion of two substrates, and
- shearing of the sealant due to differential internal pressure.

The first general mechanism of bulk relative motion of the two joined substrates is represented below and is easily visualized by considering two plates which are shifted relative to each other. This loading situation exists when a shear force is applied to one of the substrates, or when a substrate is rigidly supported and the sealant must resist its weight through shear. For this case, the distortion angle, ϕ , is reasonably constant along the length of the section. Thus the shear stress is also reasonably constant along the length.

Figure 4-10. Shear stress due to bulk substrate motion

The second typical shear loading situation is shown in Figure 4-11. This case represents differential length expansion of the two substrates. This situation often occurs due to thermal expansion mismatch, but may also occur due to other differing rates of material response to the environment. Two such situations included differing expansion due to moisture expansion of substrates such as wood, and differing rates of stress relaxation of PVC as it is exposed to the thermal environment. Whatever the cause, the critical factor is the difference of expansion, or contraction, of one substrate relative to the other. It is the magnitude of the length difference which leads to the development of shear stress. For the case of differing thermal expansion characteristics, the length difference between the substrates can be expressed as follows.

$$\Delta L = \left[\alpha_1 - \alpha_2\right] \cdot \Delta T \cdot L, \qquad \text{where: } \alpha \text{ is the thermal expansion coefficient} \quad (4)$$

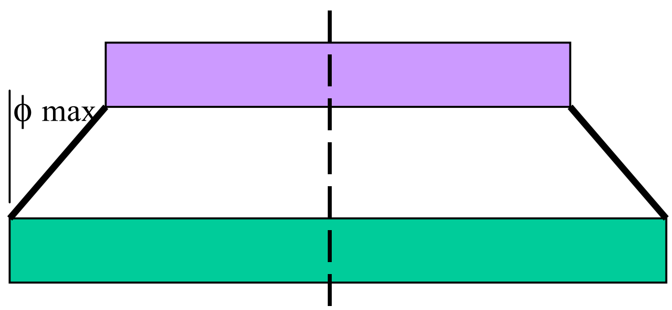

Figure 4-11. Shear stress due to differing substrate thermal expansion

It is often possible to assess this situation by considering the expansions outward from the midsections of the lengths. With this approach it is apparent that the magnitude of the distortion angle varies linearly from zero at the midpoint to its maximum value at the full length. The shear stress thus also varies linearly. The following relationship of the shear stress to the sealant thickness, beam length, and shear modulus can be shown.

$$\tau_{max} = G \cdot \tan^{-1}\left[\frac{\Delta L}{2 \cdot t}\right] = G \cdot \tan^{-1}\left[\frac{(\alpha_1 - \alpha_2) \cdot \Delta T \cdot L}{2 \cdot t}\right] \qquad (5)$$

The resistance of an IG to shear distortion often cannot be represented by a single sealant resisting the shear force. The primary and secondary sealant in many cases resists the shear forces together. Generically, this combined resistance can be considered by viewing the representation shown in Figure 4-12. Two sealants resisting the shear force usually result in a lower distortion angle than would be seen without the addition of the second sealant. The greater resistance is accomplished because the total shear force is distributed over two sealant areas, rather than just one. The amount of the total shear force withstood by each sealant is dependent on the Shear Modulus and face area of each sealant. The greater the Shear Modulus and the greater the face area, the greater the amount of force will be resisted by the sealant.

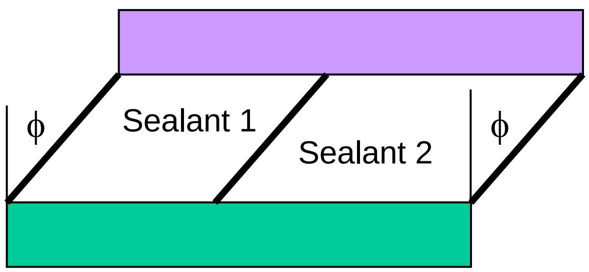

Figure 4-12. Shear stress of dual sealants of similar thickness

A more complex and in many instances more realistic configuration is shown in Fig. 4-13. In this case the two sealants differ not only in shear modulus and face area, but also in thickness. This situation would be pertinent when a variety of box and channel spacers are used. In this configuration, much greater demands are placed on Sealant 2, than was previously the case. It is required that Sealant 2 allows the same amount of linear motion as Sealant 1. Unfortunately, Sealant 2 has significantly less thickness with which to accomplish this motion. This potential problem can be understood by considering the maximum distortion angle seen by each sealant. The maximum distortion angles of the Sealants are expressed as:

$$\phi_1 = \tan^{-1}\left[\Delta L / t_1\right] \quad (6) \qquad \phi_2 = \tan^{-1}\left[\Delta L / t_2\right] \quad (7)$$

Therefore, it is clear as the thickness decreases for Sealant 2, the distortion angle increases dramatically. As the distortion angle increases, the shear stress increases proportionately. Also, since the stress in Sealant 2 is significantly higher than Sealant 1, it generally withstands the majority of the shear force. For this condition it is critical that either the Sealant 2 have significantly high strength if it has a moderate value of Shear Modulus, or it must have a very high allowable maximum strain if its Shear Modulus is on the lower end.

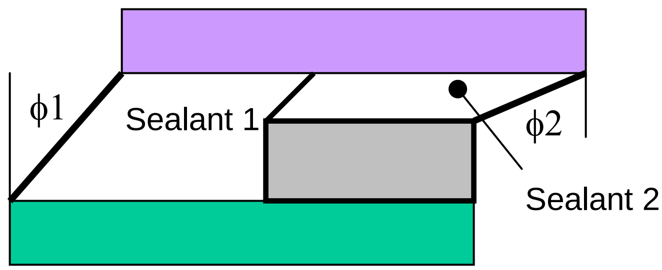

Figure 4-13. Shear stress in dual sealants with differing thicknesses

Additional considerations for shear are the end conditions of the sealant. The previous assessments were developed for the simplification of the sealant displacement being linear between the two offset substrates. Since the distortion angles are generally maximum at the extreme lengths it is important to consider this end condition. In many cases the linear assumption is a reasonable one, but there are cases where it might not be. For instance, consider the cases shown in Figure 4-14. Both the figures show sealant end conditions which are not the linear ideal. In the first figure, the slope is steeper at the substrate boundary. In the second figure, the slope is less steep at the boundary than would be estimated with a linear assumption. Such end conditions are often seen especially due to sealant contraction after initial application. Although both cases seem to be compliments of each other, the end result is the same: the maximum distortion angle is steeper than would be expected given the linear assumption. In the first case, the maximum angle occurs near the substrate interface. In the second case, the maximum angle occurs near the sealant mid-plane. To provide for such non-linearities at the end condition it is advisable to include safety factors when estimating the maximum shear angle, and thus shear stress at the boundaries.

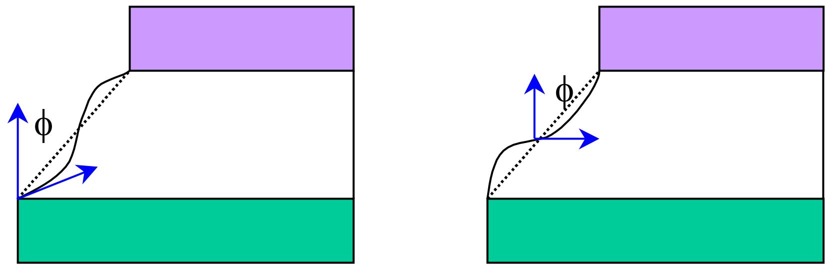

Figure 4-14. Edge effects of distortion angle

The shear effect due to the pressure differential between an IG interior and exterior will now be considered. This condition is represented schematically in Figure 4-15. The pressure differential in this case will push on the exposed interior face of the entire spacer system. Once the pressure-volume relationship is established for a given class of designs, it may be possible to predict the pressure differential using the Ideal Gas Law.

The IG pressure differential results in an effective force acting on the IG spacer. This force is resisted by shear stress across the face of the sealant. A first order approximation of this shear stress can be related to the pressure differential, the spacer width and the sealant width as follows:

$$\tau = \frac{\Delta P \cdot (SpacerWidth)}{2 \cdot (SealantWidth)} \qquad (8)$$

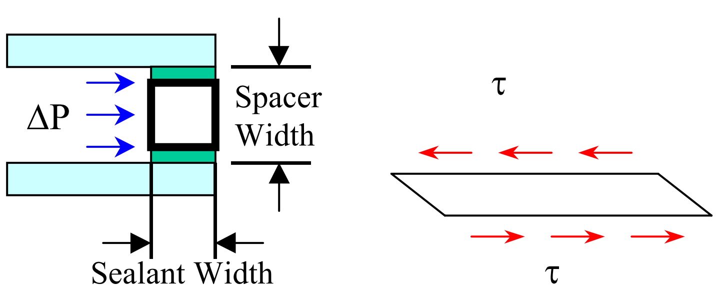

Figure 4-15. Shear stress due to internal pressurization

In some situations, it is necessary to consider the maximum shear stress as a function of not only shear loading, but also as a function of the imposed normal stresses. When complex loading situations, such as that shown in Figure 4-16, are present it is necessary to assess shear stress in terms of the maximum principal shear stress seen by the sealant.

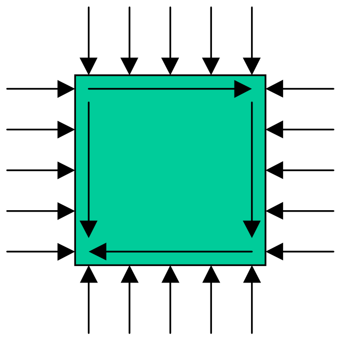

Figure 4-16. Complex stress state

An example of a situation where this approach may be necessary is the case of high pressure loading on a window due to wind gusts, in combination with a temperature extreme which is causing high thermal expansion shear stress in the sealant. Such normal stress loadings can be combined with shear stress to determine the maximum shear stress by using the following relationship. The relationship allows for the general case of normal stress loading along two axes [5].

$$\tau_{\max} = \pm\sqrt{\tau^2 + \left(\frac{\sigma_x - \sigma_y}{2}\right)^2} \qquad (9)$$

Physical Strength

The relevant material strength parameters are the ultimate shear strength, the maximum shear distortion, and the long term shear resistance, or creep behavior [6]. For sealants, the maximum shear distortion can be described by the shear angle.

The material strength can degrade through interaction with the environment. UV exposure and chemical attack can result in embrittlement and cracking, thus limiting the maximum allowable shear angle. Exposure to moisture, through either precipitation or humidity, can result in sealant modulus reduction. This reduction in modulus leads to increased movement which can cause failure.

The effective material strength can also be reduced by production issues. Internal flaws from the production process can lead to failure because they introduce two complications: they reduce the sealant's area to resist the force, and they introduce regions of increased internal stress concentration. The reduction in sealant area can lead to failure since the stress resulting from a force is inversely proportional to that area. In other words, halving the area effectively doubles the shear stress. The magnitude of stress concentrations caused by internal flaws is related to the sharpness of the voids. As the voids grow sharper, or the radii grow tighter, the stress concentration increases. Stress concentration is a significant concern, as it could easily result in the nominal stress being increased several times. An insufficiently clean material supplier process may result in a variety of contamination that could be experienced as macroscopic flaws. Cleanliness and consistency must be used in the formulation process to avoid such problems. If a good formulation has been received from the supplier, contamination may occur in the production facility as the IG spacers are fabricated. Again cleanliness and process consistency are necessary to avoid introduction of such flaws. It is also important that the IG not experience excessive shear stress prior to proper curing of the sealant [7].

The Failure Event

Shear stress results in cohesive failure either through sudden excedence of its ultimate shear strength, or through cyclic fatigue. This may occur due to high applied stress or due to high strain due to long term creep.

If a design is developed to properly account for expected environmental loading, this failure can only occur due to unexpected excedence of environmental stresses, improper fabrication, out of spec material properties, or internal flaws as a result of the production process. If excessive environmental stress is the cause, the design requirements should be reevaluated to assess whether the design exhibits sufficient safety factors. A particularly important factor in fabrication is thickness of sealant. Sufficient thickness is critical to ensure that the maximum distortion angle is not exceeded given a required amount of lateral differential movement. Out of spec material properties could be the cause if the modulus is out of spec or if the ultimate strength is out of spec. As was shown, Young's Modulus is directly related to Shear Modulus, so if one Modulus is out of spec the other is as well. Out of spec ultimate shear strength is a problem if it is sufficiently low that it does not exceed the stress imposed by its intended environment. Out of spec modulus could potentially be a problem if it is either too low or too high, depending on the design. If it is too low a greater amount of the force will be resisted by the other sealant. The other sealant may then experience loads greater than intended by the design. If it is too low it will also have more deflection which could lead to maximum strain excedence. If it is too high, the maximum shear strength may be exceeded for a given lateral deflection.

Fatigue is the gradual failure of a system due to a cyclic load. The material sees damage as peaks of cycles reach sufficient levels of stress. The damage is sufficient to degrade the material, but is not initially high enough to cause sudden failure. The damage can be observed as either loss of effective cross sectional area or as degradation of material properties. Loss of cross sectional area occurs when cracks propagate through a material, growing with each sufficiently high cyclic stress. Degradation of material properties can occur, for instance, by polymers losing cross linking bonds as sufficiently high levels of alternating stress are applied. Fracture mechanics is a useful method for modeling shear fatigue failure. The Goodman approach discussed earlier may also be applied to shear failures.

Fracture mechanics is a physics based approach to explain crack growth. The underlying principles of the theory were discussed in the previous section. The application of the theory will differ somewhat from the previous case of normal stress to the present case of shear stress. The difference results from different stress distributions and the crack path length required for failure. The stress intensity factor is related to the nature of the loading and the stress distribution. The loading case considered for shear failure is shown below.

Fracture mechanics theory is typically used by considering the rate of crack propagation as a function of an element termed the stress intensity factor. The stress intensity factor is represented by the symbol K. It is a means for expressing the forcing function of crack growth. Stress intensity factors have been developed for a variety of loading and crack propagation conditions. For crack growth, it is typically the range of stress intensity over a cycle which is viewed as the driving function in crack growth. The range over a cycle is represented as below.

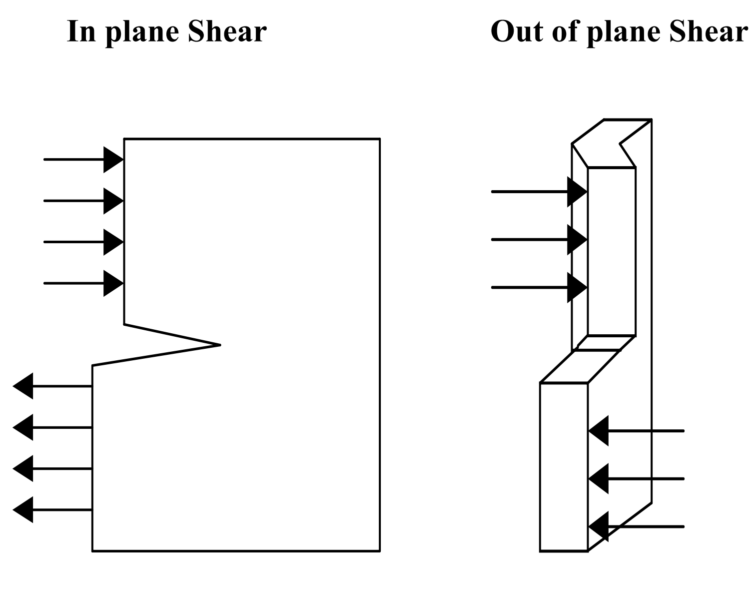

Figure 4-17. Shear failure conditions

With the above loading case defined, the stress intensity factor can then be determined from the stress distribution. The change in stress intensity factor is defined as previously.

$$\Delta K = K_{\max} - K_{\min}\big|_{cycle} \qquad (10)$$

The Paris crack growth relation again applies.

$$\frac{da}{dN} = c \cdot [\Delta K]^b \qquad (11)$$

Once again it is important to characterize the stress intensity factor range as a function of the crack length as the crack progresses. The number of cycles the material can withstand before crack failure can then be determined by either directly integrating or numerically integrating the relationship below [8].

$$a_N = \int_0^N c \cdot [\Delta K]^b \, dN + a_0 \qquad (12)$$

An additional factor which could have significant impact on sealant's cohesive shear stress performance is the degradation of the material as it is exposed to its use conditions. Environmental factors of UV, temperature, humidity, precipitation and unfriendly chemicals can significantly alter properties of improperly specified sealants. Sealant embrittlement and cracking can occur if the formulation has insufficient robustness to the environment.

Properties can degrade over time during field exposure, but in the production environment, the properties vary as well. Rather than degrading, after application sealants take a significant amount of time to properly cure. As they are curing, their properties are typically increasing to approach their properties expected for field performance. While curing it is imperative that their pre-cured ultimate strength not be exceeded.

Finally it is again worth stating that the definition of cohesive failure depends on the IG effect. The definition can be stated in terms of the size of the failure path. A failure path which is a pin hole through the width of the sealant may result in vapor passing and thus internal condensation. A failure path which covers the full cross sectional area of a sealant results in complete structural failure. The discussions of fatigue and ultimate strength excedence are applicable for considering both these cases.

As mentioned previously, if interior voids or flaws are present, sudden failure can be initiated more readily or cyclic fatigue failure can be accelerated.

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4.4 Sealant Adhesive Failure

This document discusses the adhesive failure mechanism at the interface of a sealant and an adjoining material with a specific focus on how environmental stresses impact the durability of that joint. True adhesive failure can occur due to design issues, such as sealant and substrate compatibility, manufacturing issues, such as sealant manufacturing and application processes, and environmental issues such as physical stresses experienced by the joint after being fully cured, off-gassing of low molecular weight components and chemical attack of the sealant. This paper will focus on those factors which can cause a joint to fail over time and will only discuss design and manufacturing issues in terms of their interaction with those environmental stresses causing wear-out.

Adhesive failure is defined as structural failure occurring at the interface between two material phases. The complement of adhesive failure is cohesive failure, which does not occur at the interface between two phases, but within the bulk of one phase.

Environmental Stress Quantification

As described in the two previous cohesive failure sections, coefficients of thermal expansion, gas laws, wind loads and the stress loading imparted on the IG by the sash frame all impose mechanical stresses on the adhesive joint. In addition to these stresses, other environmental factors will stress the adhesive joint chemically. The stressors acting on the sealant/substrate interface include:

- Shear stress, which stretches a sealant parallel to the substrate.
- Normal stress, which stretches or compresses perpendicular to the substrate.
- Photons (UV and IR), which initiate and/or accelerate chemical attacks.
- Solvents (water and/or hydrocarbons), which soften and plasticize.
- Environmental chemicals (oxidizers, reducers, acids, bases), which alter the chemical structure of either the substrate or the sealant.

Design and manufacturing issues, such as material compatibility, manufacturing and assembly process conditions, and contamination of the sealant and/or substrate (silicones, hydrocarbons, water, debris, etc.) can enhance or reduce the effect of these environmental factors on the IG unit by several orders of magnitude and must also be considered when evaluating the durability of an insulating glass unit.

Environmental to Physical Stress Translation

The Griffith-Irwin fracture theory, applied to a joint comprising two phases [1], describes the stress required to propagate a fracture, (σ_f), in terms of a constant,(k), the elastic modulus, (E); the fracture energy, (G); and the critical crack or defect length, (l):

$$\sigma_f = k\left(\frac{EG}{l}\right)^{1/2} \qquad (1)$$

G is further understood to be a function of γ_s [2, 3], the surface energy, and other energy absorbing processes, ψ, such as plastic and viscoelastic deformation:

$$G = \gamma_s + \psi_{plast} + \psi_{v/e} + \ldots \qquad (2)$$

Usually, ψ is several orders of magnitude greater than γ, so G is approximately ψ, although processes that enhance or degrade γ may have dramatic effects on adhesion as γ and ψ are often coupled. Stated another way, stronger bonds (increased γ) may lead to much larger increases in fracture energy (G) because they allow much more bulk energy dissipation (increased ψ) during fracture.

The effects of numerous environmental stresses on adhesion durability can therefore be understood in terms of the effects those stresses are predicted to have on local modulus (E), surface energy, (γ), energy dissipating capacity, (ψ) and defect size (l).

Physical Strength

With respect to adhesive strength, the relative strength parameters are (γ_s), (ψ) and (l). Failures will propagate in the direction from the ends of existing cracks wherever the local term:

$$\frac{E(\gamma_s + \psi)}{l} \qquad (3)$$

is lowest [2], but if the term is low due to the sealant having a low modulus (E), then the fracture will typically progress through the sealant causing a cohesive, rather than adhesive failure. Shear and normal mechanical stresses are not expected to significantly alter the surface energy (γ_s) over time, but the bulk energy dissipation capacity (ψ) of the sealant is expected to be reduced, and the lengths of the existing defects (l) at the interface are expected to grow.

Photonic stresses (ultraviolet and infrared) are expected to initiate, promote and accelerate chemical attack of the sealant. UV photons are effective at breaking chemical bonds leaving highly reactive end groups available to recombine with nearby molecules. IR photons (heat) greatly accelerate all chemical reactions because the probability of high-energy encounters between molecules increase rapidly with temperature, approximately as $e^{(-K/T)}$[4]. The specific reactions taking place are beyond the scope of this paper, but are highly dependent upon the wavelength of the photon, the activation energy of the chemical bond exposed to that photon, the atoms or molecules surrounding the bond when the photon is absorbed, the mobility of those molecules near the bond and the activation energy of any of the potential bonds with surrounding molecules. These reactions typically alter the energy dissipation capacity (ψ), and the surface energy (γ_s). The reactions will also introduce point defects, but until very many of these coalesce, (l) will remain insignificant compared to the defects introduced through other means. The direction that ψ and γ_s move, moreover, cannot be determined until the specific, often multiple and competing, reactions are enumerated. Because of this, sealants often increase in bond strength for a period of time, peak, degrade and eventually fail.

Stresses induced by increased solvent should increase the energy dissipation capacity (ψ), and may decrease the surface energy (γ_s). The effects of solvent levels are therefore not monotonic.

There appears to be an "optimal" level of solvent above which the surface energy is reduced to the point of failure and below which the energy dissipation capacity of the sealant is reduced to failure.

Stresses induced by environmental chemicals work in conjunction with the photonic stresses to generate molecular contamination of the sealant. Generally these contaminant compounds have significantly different properties than the sealant material from which they were generated. Until the specific reaction products are known, it is impossible to determine how the adhesive strength of the sealant will be affected. These reactions will primarily alter ψ and γ_s, but the direction these properties will move is dependent on too many variables to be generalized within the scope of this paper. As previously mentioned, the adhesive properties of the sealant do not necessarily vary monotonically. They frequently experience a 'curing' period in which the adhesive bond strength rapidly increases, followed by a much longer period during which chemical attack slowly degrades the bond strength.

The Failure Event

Sealant failure, whether cohesive or adhesive, propagate along the path of least resistance. In other words, the fracture will continue in whichever direction the semi-local term:

$$\frac{E(\gamma_s + \psi)}{l} \qquad (4)$$

is smallest. The nature of the failure is highly dependent upon the variables in this term. This section will lay qualitatively lay out the expected macroscopic differences between adhesive failures dominated by each of the terms in the above expression.

<u>Modulus:</u>

When the fracture stress is lowest due to a low value of E, the resulting fracture will propagate through either the glass or the sealant phase, not along the adhesive interface. This mode of failure is discussed in greater detail in sections 4.2 and 4.3.

Surface Energy:

The surface energy term (γ_s) almost never dominates the above expression because to a first approximation it can be considered negligible compared to the energy absorbing processes (ψ). In reality, these two terms are almost always strongly coupled. If the surface energy is zero, then it really doesn't matter that the sealant can dissipate an enormous amount of energy – it won't need to. Similarly, if the surface energy is sufficiently high, then all of the energy dissipative capacity of the sealant will be utilized before the bond breaks. Failures caused by low γ_s exhibit pure adhesive failure. The sealant may retain all of its original pliability, but it just didn't seem to stick to the surface. The primary causes for this type of failure are material choice, surface contamination during manufacture and/or improper application temperature and pressure.

Energy Dissipation:

The expression above is dominated by the energy dissipation term (ψ). Sealants with this term maximized require amazingly low bond energies to create a highly durable bond. One can create a super tape with standard low-tack adhesive on a highly visco-elastic web. Even though the adhesive is not particularly strong, the tape is as a whole is extremely strong due to the very large energy dissipative capacity of the web material. Bonds that fail due to low ψ typically exhibit embrittled adhesive. The primary causes of this type of failure is material choice (too brittle) and chemical attack, often promoted by solar irradiation and heat (UV and IR).

Defect Length:

For the purposes of this paper, there is no such thing as an initiation of a fracture. All failures begin at pre-existing defects. As one can see, if the defect length is zero, then an infinite amount of stress would be required to fracture the material. There is generally no such thing as a defect-free material, however, so this point is largely academic. The larger the defect, the less energy is required to break adjoining bonds. Post-mortems of bonds that fail due to large defect lengths may or may not reveal the source of the crack initiation. These defects are most often introduced during the manufacturing process and include entrained gas, dust, and other contaminants. Crystal grain boundaries within the sealant also constitute defects and again are introduced during manufacture. The primary cause of this type of failure is poor manufacturing understanding and/or process controls.

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4.5 Structural Glass Failure

There are a number of stresses that glass in a window experiences during its service life. These stresses originate from both the environment and the window itself. Environmental stresses include temperature, wind loads and chemical attack. Stresses from the window on the glass include the pressure of a dry glazing on the edge. The glass selected for use in a window must have sufficient strength to withstand the reasonable environmental stresses that the window would experience. It also goes without saying that the window should be designed and installed so as not to apply any unreasonable stresses to the glass.

Environmental Stress Quantification

The relevant environment forcing functions are solar flux, air temperatures, barometric pressure fluctuations, relative humidity, precipitation and wind loads. The forcing functions are dependent upon season and geographic location.

Environmental to Physical Stress Translation

The environmental forcing functions cause the glass lites of a window to continuously experience plate bending while simultaneously being heated unevenly across their surfaces.
The glass lites and the IG gas content are heated by the solar flux, indoor and outdoor air temperatures, and direct conduction via the window frame and the spacer/sealant. The heating of the glass (and thus the thermal expansion) is very uneven thanks to the shading effects of eaves, the window frame itself, and the thermal conduction of the frame and spacer.

The IG gas temperature variations and barometric pressure fluctuations create large pressure differences between the IG air space and the atmosphere. Wind gusts directly bend the glass lites.

When we add the fact that the window frame and IG spacer mechanically constrain the bending motions of the glass lites, the result is a very large, non-uniform distribution of strain energy in the glass lites.

A sufficient crack in the glass at a point of high strain energy can result in glass breakage. High relative humidity can accelerate crack growth rates.

Physical Strength of Glass

Glass used in residential and commercial windows is primarily the "soda-lime" recipe, consisting principally of silica sand, soda ash, and lime. A small amount of magnesium oxide is added to the mix to retard water corrosion.

Glass fails in a brittle fashion; its elastic modulus is in the range of 10^7 psi, and it has a thermal coefficient of expansion of about $9e^{--6}$/°C.

Glass has very poor yield strength compared to its theoretical maximum. Its yield strength is an extrinsic property, being highly dependent upon surface crack density. But glass can be significantly strengthened by tempering, heat-treating, chemical treating and laminating. These processes place the surface of the glass in compression, which limits crack growth by keeping the plate surface in compression even under moderate bending loads.

But there is much more involved in understanding the "strength" of a lite of glass than knowing its elastic modulus and yield strength. Starting from the thin plate equation and assuming isotropic plate material, it can be shown that under a uniform pressure difference across the face of a plate, the deviation from flatness of the plate is simply described.

Thus we qualitatively describe the deviation from flatness as being proportional to the pressure difference and the 4th-power of the width of the plate, while being inversely proportional to the elastic modulus and the cube of the plate thickness.

The Failure Event

While a useful starting point, the thin plate equation is applicable only for small bending motions of plates having reasonable isotropic properties. Using finite element analysis (FEA) models, designers can routinely predict the strain distribution across glass lites (using assumed non-isotropic properties) under any given environmental and boundary conditions. In principle, designers can select the glass geometry and glass treatment type to endure almost any reasonable situation.

However, glass does form surface cracks extremely easily, be they from mishandling, wind-blown debris, or perhaps even from tiny defects at the time of casting and annealing. Flaws on the glass surface cause a concentration of stress at the crack tip. For Griffith flaws, the stress concentration is given by:

$$\sigma_{max} = \sigma_0 [1 + 2(a/\rho)^{1/2}] \qquad (1)$$

where:

σ_{max} = maximum stress
σ_O = applied stress
a = flaw depth
ρ = flaw radius

When the glass in an IG experiences a serious bending load, stress is already non-uniformly distributed across the sheet. At high points of stress, the glass surface may pass from compression to a state of tension. At cracks under tension, the stress concentrates at the edges of the cracks, breaking chemical bonds in that location and slowly lengthening the cracks. This increases the stress concentration in that area of the lite. At some point under severe loading, a crack will suddenly propagate and grow at high speed, resulting in catastrophic failure.

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4.6 Failure due to Excessive Water Vapor in the Airspace

The failure of an IG unit due to excessive water vapor in the airspace is perhaps the most catastrophic of failures, barring glass breakage. When excess vapor is present in the airspace, condensation on the interior of the glass panes occurs at low temperatures. This “fogging” becomes frost in the winter and a customer will notice the very obvious failure.

Upon temperature increases, the moisture phase changes back to its gaseous state and it is not uncommon for unremovable “spots” to remain, because the latter are within the IG unit.

Since internal condensation is so visible when it occurs, other failures, such as the external moisture problems resulting from IG unit “dishing” (which is caused by net gas loss from the IG air space), become secondary considerations.

Environmental Stress Quantification

The huge water vapor partial pressure difference between the desiccated airspace and the normal outdoor environment creates a thermodynamic driving force for mass transfer to occur.

Environmental to Physical Stress Translation

Water vapor will eventually penetrate into the airspace; it is the manufacturers’ responsibility to slow the process down as much as possible. Since most companies use a viscoelastic polymer as a primary seal, the vapor has a pathway, albeit a very tortuous one, through the long, intertwined molecular chains. One of the most important material properties to define is the polymer’s water vapor transmission rate. This rate allows a calculation as to the time it takes vapor to transfer through the polymer. On a microscopic level, a water molecule is adsorbed onto the mesh of polymer chains on the surface exposed to the environment. It then follows a relatively random path through the polymer chains, jumping from void to void, that inexorably leads it towards the side of less vapor concentration, where it finally exits the polymer into the airspace. Energy is supplied for this jumping by random molecular collisions.

The water vapor transmission rate through a sealant is in general a function of sealant material temperature, adsorbed water content, and mechanical strain of the sealant material [1].

Physical Strength

Various materials and designs are used in an attempt to slow down the water vapor molecule on its way to the airspace. Most designs allow for some water vapor to enter the airspace, where it is absorbed into a desiccant. Desiccant is placed in the IG airspace to remove the excess moisture from the manufacturing process and from environmental vapor penetrating the seal in the manner described above [2].

The Failure Event

The accumulation of water vapor in the IG space is a combination of the influx of water vapor through the sealant and outgo of water vapor into the desiccant:

$$dn_w/dt = -P_w\,(A/l)\,\Delta p_w + c\,dm_w/dt \qquad (1)$$

where

t = time

n_w = quantity of water vapor in the IG airspace

P_w = permeation coefficient of water vapor through the sealant

A/l = ratio of surface area to path length

Δp_w = water vapor pressure gradient across the sealant

c = number of moles of water per unit mass (a constant)

m_w = mass of water absorbed by the desiccant

If the moisture vapor transmission rate into the IG exceeds its design boundaries, the desiccant will eventually lose its ability to absorb any more water vapor: it becomes saturated. When this occurs, the airspace fills up with water vapor and internal condensation can occur, usually at low temperatures. As the airspace continues to gain moisture, the temperature at which moisture condenses out continues to increase. The temperature that moisture spontaneously condenses out of the air is called the saturation temperature, or dew point. Most IG units are manufactured to a target airspace dew point of -90°F. If the dew point ever increases through excessive moisture vapor transmission to -20°F, the unit is considered failed. A temperature of -20°F can readily occur in the northern United States and Canada during a normal winter. This is how internal frosting can occur, which is a very noticeable failure.

Summary

The water vapor will penetrate into the airspace over time. If there is a slow enough transmission rate and enough desiccant to absorb excess water, the life of the unit should be sufficiently long to achieve reasonable customer satisfaction. If any manufacturing defects occur, or the above conditions are not met, the vapor saturates the desiccant, and a catastrophic failure occurs, rendering all other failure modes secondary. Frost rings occur in the winter, or over a long period of time enough water vapor in the airspace causes condensation on the inner panes of glass at higher, non-freezing temperatures.

References

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4.7 Failure due to Argon Loss

Overview

Concave and convex bending of insulating glass (IG) lites is a normal occurrence since the barometric pressure and the gas pressure within the air space of the IG unit are rarely in a state of equilibrium. This temporary flexing phenomena is often referred to as “dishing” [1].

A state of permanent concave bending of IG units occurs when the gas content within the IG space is significantly lowered. The term “collapse” is often used to describe this phenomena [1]. This results in expensive field service calls. Viewing is distorted and the thermal conductivity of the center portion of the IG jumps precipitously (U-value increase). Water vapor condenses under temperature conditions the product commonly experiences. One result is indoor “frost rings” or water on the window in wintertime. Another result is water condensation on the outdoor surfaces of windows in air-conditioned rooms during the summer time.

"Collapse" was once cause for concern. Root causes of "collapse" were many: Poor choice of desiccant, too much desiccant, filling the IG air space at high temperatures, or filling the IG air space with an atmosphere of high relative humidity (whereupon the dessicant removes a significant portion of the IG gas pressure). These process and design issues were resolved many years ago.

The “collapse” problem returned in the 1990s. Manufacturers began to fill high-performance IG units with chemically-inert, low-thermal-conductivity gases, with the goal of significant U-value reduction. Since argon is an effective insulator, is chemically inert, and is fairly inexpensive, it is the gas-fill of choice (though not the only choice).

However, argon leaves the IG space at a higher rate than oxygen and nitrogen can replace it, which results in lowered gas content within the IG air space (and thus "collapse"). This process is expected to occur over a time span of decades through a judicious choice of sealants.

With the sufficient accumulation of defects, this gas exchange process may occur on a time scale of months or years.

Environmental Stress Quantification

There are enormous partial pressure differences across the boundary of the sealant, between the IG gas space and the external atmosphere for argon, nitrogen, oxygen, and water vapor.

The previously-noted environmental stresses of barometric pressure, air temperature, solar flux, and relative humidity operate in tandem with the partial pressure forcing functions. They cause variations in the internal pressure of the IG unit and continually stress the sealants.

Environment to Physical Stress Translation

All polymeric sealants will pass gas molecules to some degree when a partial-pressure gradient exists across the sealant boundary (permeation). Dalton's Law of Partial Pressures cannot be avoided.

Gas molecules move through a barrier according to a flux-type equation, where the rate of gas transfer is directly proportional to the size of the pressure difference across the faces of the sealant:

$$dn_x/dt = -P_x\,(A/l)\,\Delta p_x \qquad (1)$$

where:

t = *time*
n_x = *a specified quantity of gas "X" (e.g. moles of argon)*
P_x = *permeation "coefficient" for gas "X" through the barrier*
A = *exposed surface area of barrier*
l = *path length through the barrier*

Δ***px*** = *pressure gradient of gas "X" across the barrier*

However, the sealants suffer continuous and variable mechanical and thermal stresses over a wide temperature range while enduring long-term UV bombardment and water vapor attacks. This has been noted in previous papers in this chapter. There is no reason to believe that permeation coefficients, exposed surface area and gas path lengths are unchangeable.

Physical Strength

IG sealants are normally composed of polymeric-type materials which allow the transfer of gas molecules. However, primary sealants are chosen to have extremely low permeation rates in their unstrained states and normal operating temperature ranges. Considering the sealant as an isolated component, gas exchange should not be an issue so long as workmanship is maintained at an adequate level.

However, the sealant is part of a total system (the IG) interfacing with demanding external forcing functions. The permeation rates of sealants are functions not only of their isomeric composition, but also of the sealant temperature, adsorbed water content, mechanical strain, and accumulated defects such as cracks and voids.

Sealants must have good, tight, adhesion to the glass. If the sealant/glass adhesion boundary suffers enough damage (which is quantitatively unknown to us) the resultant cracks will allow gas exchange between the IG space and the atmosphere.

Sealants must be able to withstand the steady tensile, compressive and shear stresses the environment inflicts upon them. They must not suffer excessive cohesive damage. If they do, it is possible that permeation coefficients are changed, or gas path lengths through the sealant are significantly shortened.

The Failure Event

Partial-pressure gas transfers will occur via permeation. An unknown percentage of IG lites will gradually and permanently "collapse" at room or colder temperatures. There will be optical distortion. There will be resulting increases in U-values, significantly above those of dry-air filled units, which defeats the intended purpose of using inert gas for insulation.

Summary

Field failure rates of specific IG products are not publicly shared information. The net gas loss problem is due to sealant/spacer failures, be it design, materials, manufacturing, or accumulated defects from extreme environmental cycling. Based upon work performed by the National Research Council [8], there are variations in performance among IG designs and implementations in terms of argon gas retention.

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5. Environmental Stressors

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5.1 Summary of Environmental Stressors

The robustness of the IG design is reflected by the bell curves of stress and strength. The area of overlap between the stress and strength curves will dictate the amount of failures expected. The environmental stressors enter this discussion as they provide the driving input to the stress distribution. The environmental stressors are translated to the physical stresses through the physical failure mechanisms.

It is thus important to consider what environmental stressors are drivers for the physical stresses. It is also important to quantify the magnitude of the stressors as well as their variability. Figure 5-1 is an attempt to represent the relevant environmental stressors.

The quantity of normal stress the IG sealant will experience is driven by several environmental factors. These factors, which will drive both cohesive and adhesive failures are as follows:

- Temperature
- Barometric pressure
- UV
- Relative Humidity
- Wind loading

Temperature will drive sealant normal stress due to its effect on the pressurization of gas within the IG. This temperature driven pressurization will cause torque induced flexure of the sealant as well as uniform stretching of the seal as the glass tends to push outward. The flexure will induce a normal stress which is linearly distributed across the sealant. The uniform stretching will result in a uniform tensile stress field. The total magnitude of the normal stress due to temperature will be the addition of these two stress fields. Maximum, minimum, and average temperature are all relevant. Maximum and minimum temperatures dictate the extrema and the range of the resulting stress distributions. These will drive the cyclic fatigue response of the system. The average temperature will be relevant to the long term steady state response of the system. In particular, the average temperature is relevant to quantify the long term effects of creep on the sealant.

Failure Mode	Environmental Stressor	Stressor Level	Rationale
Seal Cohesive Normal Stress	Temperature	Max, Min, Average	Flexure
	Barometric Pressure	Max, Min, Average	Flexure, distributed Compressive Stress
	UV	Total Exposure	Strength degradation
	Relative Humidity	Max, Average	Sealant Modulus reduction
	Wind Loading	Max, Average	Flexure, Distributed Compressive Stress
Sealant Cohesive Shear Stress	Temperature	Max, Min	Differentation elongation of materials
	UV	Total Exposure	Strength degradation
	Relative Humidity	Max, Average	Sealant modulus reduction
Sealant Adhesive Normal Stress	Temperature	Max, Min, Average	Flexure
	Barometric Pressure	Max, Min, Average	Flexure, distributed Compressive Stress
	Relative Humidity	Max, Average	Sealant Modulus reduction
	Wind Loading	Max, Average	Flexure, Distributed Compressive Stress
	Precipitation	Total Exposure	Adhesive degradation
Sealant Adhesive Shear Stress	Temperature	Max, Min	Flexure
	Relative Humidity	Max, Average	Sealant Modulus reduction
	Precipitation	Total Exposure	Adhesion degradation
Spacer Structural	Temperature	Max, Min, Average	Flexure stress
	Barometric Pressure	Max, Min, Average	Flexure, distributed Compressive Stress
	Wind Loading	Max, Average	Flexure, Distributed Compressive Stress
Dessicant Saturation	Temperature	Max, Min, Heat Deg Day	Flexure Stress effect on MVTR
	Barometric Pressure	Max, Min, Average	Flexure, Uniform Stress effect on MVTR
	Precipitation	Total Exposure	Diffusion relationship
	Relative Humidity	Max, Average	Diffusion relationship
	Wind Loading	Max, Average	Flexure, Uniform Stress effect on MVTR
Glass Structural Failure	Temperature	Max, Min	Stress effect on crack growth
	Barometric Pressure	Max, Min, Average	Stress effect on crack growth
	Wind Loading	Max, Average	Stress effect on crack growth

Figure 5-1. Environmental Stressors

Barometric pressure and wind loading drive the sealant normal stress by causing a pressure differential between the exterior and interior of the IG system. This pressure differential results in IG internal volume expansion and contraction, which leads to flexure of the spacer system. As with temperature, the maximum and minimum values will dictate the extrema and range, for purposes of understanding the sealants' fatigue response. The average value will be relevant to long term creep response. The same parameters are also important for understanding the effect of wind loading. The minimum value is omitted in this case as the base line case of no wind is assumed. Relative humidity has an effect on normal stress since the amount of moisture effects the modulus of the sealant. Variation in the modulus will cause differences in the normal stress response. The greater the amount of humidity, the more the modulus will be degraded. The maximum value of RH is important to understand the peak effect on modulus. The average value is important to understand the long term quasi-static effect.

UV exposure tends to degrade the ultimate strength of the sealant; it also effects the modulus by making the sealant more brittle. The material will continue to degrade as it is exposed to photons, thus the total exposure of UV is relevant. The amount of precipitation is also relevant, as direct exposure to liquid often tends to degrade sealant structural properties

The response of the IG to sealant cohesive shear stress is dictated by the following environmental factors:

- Temperature
- UV
- Relative humidity

The magnitude of temperature is important as it causes differing expansions of materials due to their differing coefficients of thermal expansion. The differing thermal expansion will cause maximum strains at the boundaries of the sealant. The expansions will be at their maximum for the maximum and the minimum temperature which the IG experiences.

Total UV exposure will dictate the modulus of the sealant. The modulus degradation will dictate how much stress will be developed in the sealant for a given amount of differential expansion. Modulus is also a function of moisture, the greater the amount of relative humidity, the less stress will be developed for a given amount of temperature deflection. Relative humidity will also have an effect on wood based substrates. For the case of wood based materials, the amount of expansion due to moisture is often greater than the amount of expansion due to temperature differentials. The average RH is necessary to understand the quasi-static response of the system. The maximum RH is necessary to study in order to understand the effect of maximum expansion of wood based substrates.

Sealant adhesive shear stress is driven by the stressors as stated for cohesive shear. An additional environmental stressor is precipitation. Total precipitation is again relevant, as exposure to liquid water often tends to degrade the sealant structural properties.

Structural failure of the spacer is driven by the maximum amount of stress as well as the range and duration of cyclic loading. This stress is developed due to the fluctuations of pressure differentials across the IG. The parameters which cause these stresses, which were discussed for the case of sealant cohesive stress, are:

- Temperature
- Barometric pressure
- Wind loading

Glass structural failure is also driven by the stresses manifested from pressure differential cycling of the IG. Again, temperature, barometric pressure and wind loading are seen to be driving factors. Although the environmental stressors are the same as for the spacer, the manner in which the stresses manifest themselves in failure is different. Stresses developed in the region of the spacer may manifest in failure as edge defects of the glass grow to failure from stress concentrations. Alternatively, the stresses developed with the glass may result in failure if interior voids are present or if excessive wind loading is present.

The time as which the desiccant becomes saturated may be accelerated by the following environmental factors:

- Temperature
- Barometric pressure
- Precipitation
- Relative humidity
- Wind loading

It is hypothesized that temperature, barometric pressure and wind loading may accelerate the rate of desiccant saturation by increasing the rate of moisture vapor transmission across the sealant. This is speculated to occur by the stress field stretching the material, thus expanding the area of effective vapor transmission paths within the sealant. Testing is required to validate this hypothesis. Precipitation and relative humidity increase the rate of desiccant saturation by increasing the driving potential of moisture across the sealant.

5.2 Quantification of Environmental Stressors

The durability of an insulating glass (IG) unit follows a standard materials, process and design continuum. The manner by which these three elements interact with each other and with the environment will determine the durability of an IG. The environmental stressors which have the most impact on IG durability are: temperature, barometric pressure, UV, RH, wind loading and the presence of water (in both precipitation/liquid form, as well as relative humidity). A majority of the impact from the environmental stressors on IG durability occurs during three stages: component manufacturing (i.e. desiccant manufacturing), IG assembly and service life.

It is the intent of this section to demonstrate how variations in the environment can be quantified and summarized. This information may then be used in the development of physical stress models, accelerated test methods, used to validate IG failure data or to validate the presence of failure modes.

To demonstrate the method of environmental stressor quantification, the combined daily barometric pressure and temperature variations will be summarized in a manner conducive for input into a stress-strength model. It is believed that a primary source of IG failures is the repeated flexure of the sealant, as well as deforming the sealant beyond its nominal elastic limit.

Simple application of the ideal gas law, in Equation 1, can be considered when developing the pressure change within the IG.

$$\mathbf{PV=NRT} \qquad (1)$$

It would be ideal if this relationship, combined with data available from the National Weather Service database, would permit us to determine the pressure change in an IG due to the environmental contributions. Unfortunately, without knowing the characteristics of the specific IG (sealant modulus, plate deflection, etc.), we cannot determine the actual pressure difference between the inside and outside of the IG. However, to bound the problem, if we consider an infinitely stiff system, our formulation would simply reduce to a rigid volume calculation, under the ideal gas law:

$$\mathbf{P_0/T_0=P_1/T_1} \qquad (2)$$

Where:

P_0 and T_0 are the barometric pressure and temperature of the IG unit at the time of IG assembly.

P_1 and T_1 are the barometric pressure and temperature of the IG unit at the time of measurement.

This calculation could later be adjusted to compensate for volume increase due to flexure in the sealant and the glass lites, once the pressure-volume relationship is specified for the IG unit.

Quantification of IG Internal Pressure Variation

For the purposes of this calculation, we assumed a rigid volume, a manufacturing temperature of 23° C, and the *30-year average* barometric pressure in Minneapolis, MN (14.29 psi). The pressure and temperature contributions to the internal IG pressure are then studied for two regions, to demonstrate an "environmental harshness" on an assembled IG. Even this is a gross simplification. While the manufacturing plant may be maintained at a relatively constant temperature, it is unlikely that the daily barometric variations be controlled in any manner. Thus a broader statistical study may be required to superimpose the barometric pressure at the time of manufacture with the daily variations in barometric pressure.

The internal temperature of the IG is taken to be the simple average of the outside air temperature and 23° C as the interior house temperature (i.e. any additional solar heating of the gas within the IG is ignored).

Using the data from the National Weather Service database [1], 1961-1990, relative to manufacture on an "average day" in Minneapolis, MN (described above), we determine the pressure difference between the inside of a rigid volume and the outside barometric pressure. A rigid volume "IG" in these two regions (Minneapolis, MN, and Phoenix, AZ) would exhibit the internal pressure behavior shown in Figure 5-2**.** A few things are evident from the distribution in figure 1; Minnesota has more variation in pressure deviation, while the distribution of pressure deviation in Arizona is shifted so that there is, on average, a constant pressure offset.

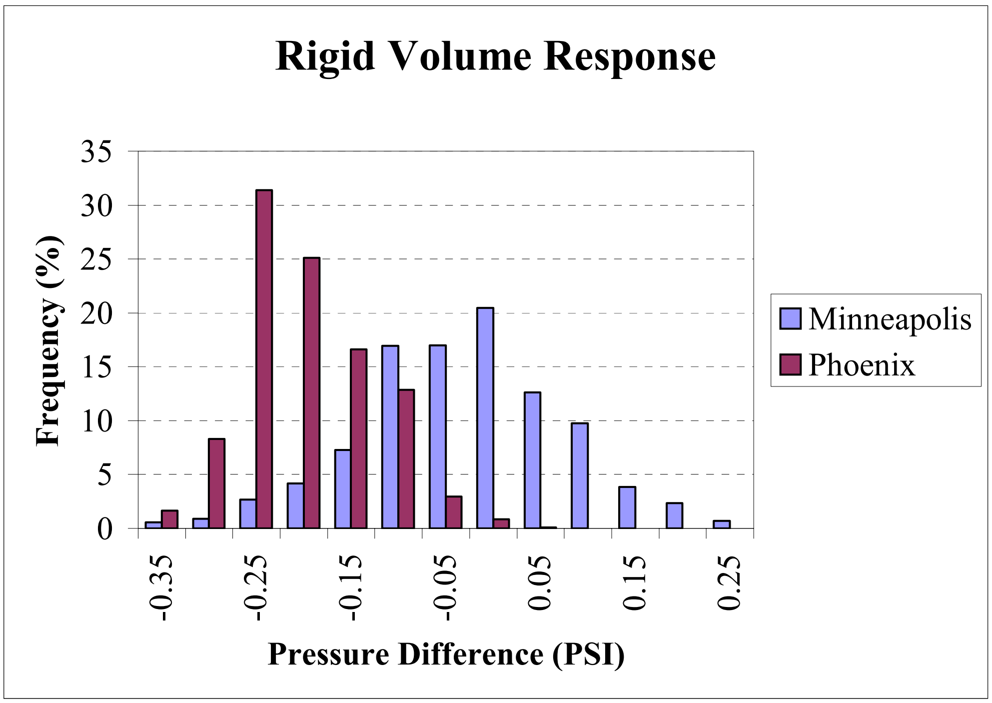

Figure 5-2. The pressure which a rigid volume would experience, due to environmental factors, for a unit manufactured in Minneapolis, MN. From this plot, it seems that a pre-emphasis, targeted for a specified sales region, may be desirable during IG manufacture.

Other Environmental Factors

In addition to the internal forces due to pressure and temperature, which may damage a unit, other factors, such as air temperature, relative humidity, wind speed and direction will all have an effect on the reliability of an IG. Further, these variables must be quantified if one is to apply the correct lite and sealant flexure, to obtain the subsequent volume change of an IG unit (as described in Chapter 6).

Air temperature and relative humidity (RH) will both affect the modulus of the elastomer sealant, and may both contribute to the deterioration of these materials.

The wind speed and direction may give insight into additional loading on certain units within the building structure, and these environmental factors may show correlation with field failure data.

Fortunately, these physical parameters, and many others, can be captured and catalogued from the National Weather Service database [1], as is shown below, in Figures 5-3 through 5-6. These plots were generated from data in the 1961-1990 NCDC database.

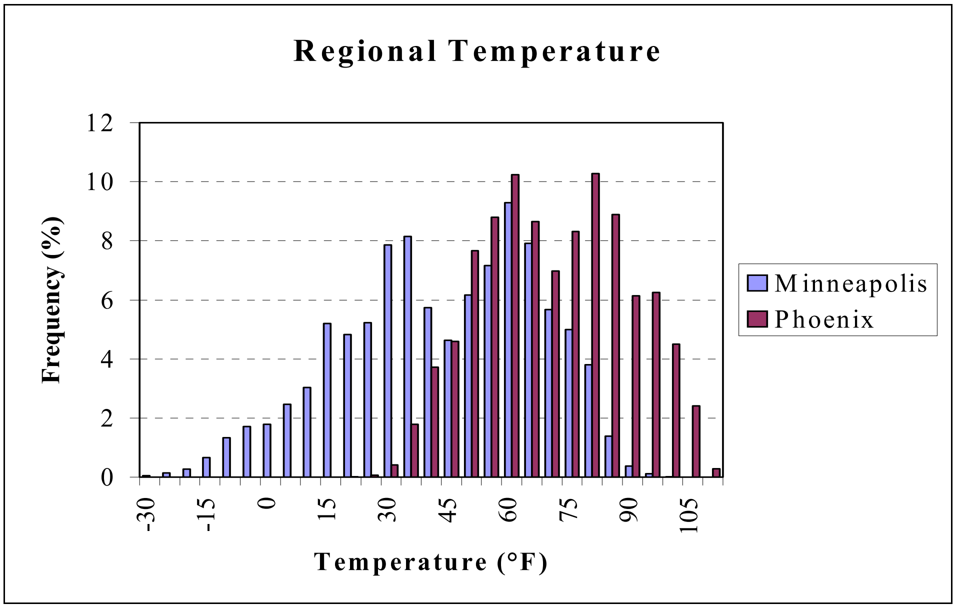

Figure 5-3**:** A regional temperature histogram for Minneapolis, MN and Phoenix, AZ. Note the substantially broader distribution of temperatures found in the Minneapolis area.

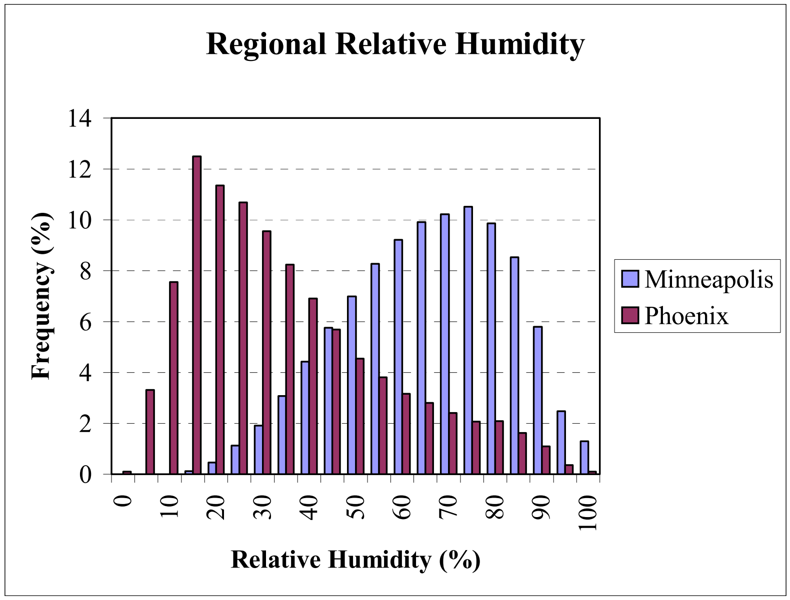

Figure 5-4**.** The regional relative humidity for Minneapolis, MN and Phoenix, AZ. The higher RH in Minneapolis could be expected to increase degradation of the IG due to water vapor infiltration.

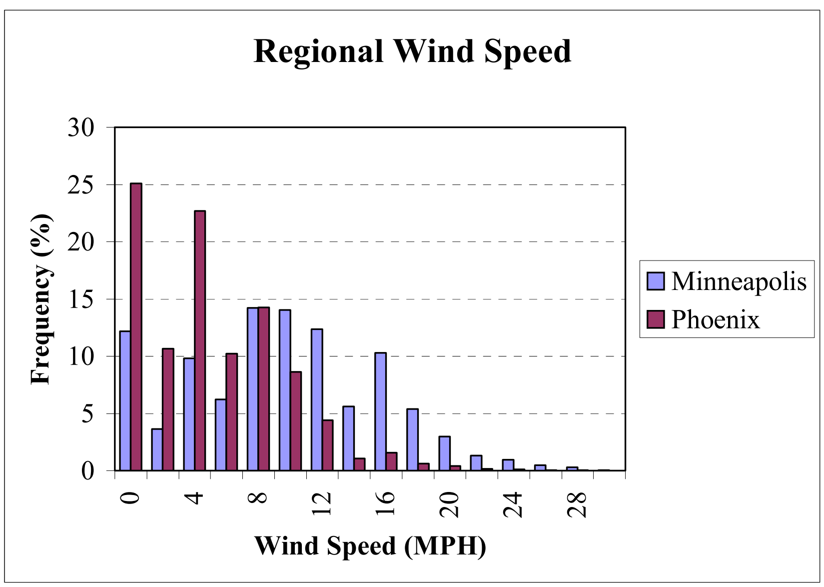

Figure 5-5. A histogram of wind speed occurrence for two regions, Minneapolis, MN and Phoenix, AZ, for winds from the West through North (270°-360°). Again, Minneapolis seems to indicate a harsher environment, this time due to wind loading.

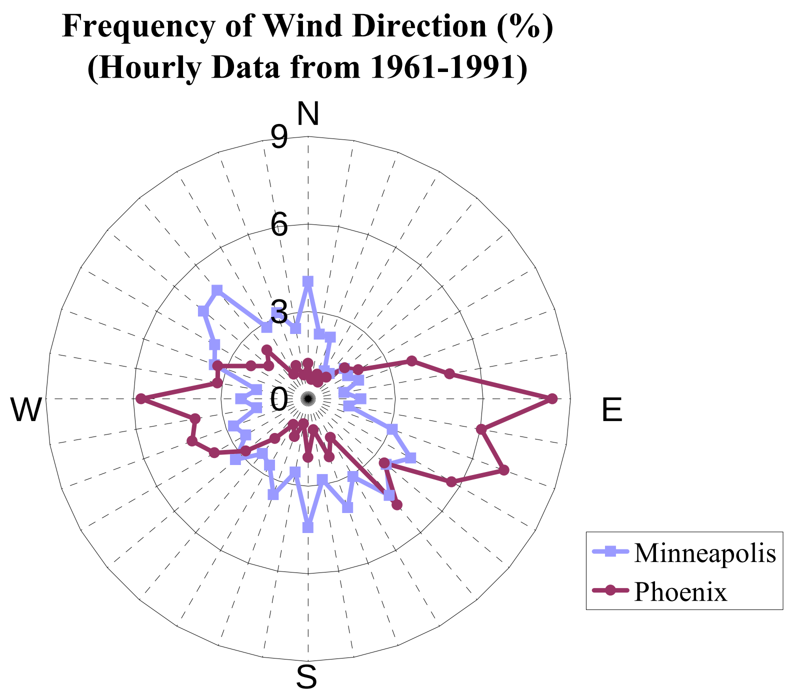

Figure 5-6. A plot of wind direction occurrence for the two regions, Minneapolis, MN and Phoenix, AZ. Note: the direction shown is a wind from that direction (e.g. a wind direction of 270 is a wind from out of the West).

Conclusions

From these examples, one can see that it is possible to quantify potential sources of environmental stress to which an insulating glass unit is exposed.

In the first example, we observed the potential forces on a rigid volume. In practice, these would be reduced by the flexure of the sealant and glass lites (which will be modeled in Chapter 6). A rigorous modeling process will require that we first determine the contribution of this function, through empirical measurements.

In the latter examples, we simply summarized a few examples of the existing environmental data, which can be found in the National Weather Service database [1]. Without a hypothesis being tested, these data summaries do not stand alone. However, since we know that outside of material, process and design, the environment drives IG durability. Section 5.1 has laid out several failure modes and environmental factors that drive the failure occurrence. These are the hypotheses that need to be tested. With data that is available from sources such as the 1961-1990 NCDC database, theoretical models can be built and validated by pairing results with environmental data and IG failure data obtained from actual field service work or accelerated test data.

5.3 Stressor Function Development

Introduction

In this section we continue to lay the groundwork of a methodology leading to the generation of insulating glass (IG) reliability estimates for specific geographic regions, based upon IG dimensional and modulus information and the United States National Weather Service database.

Environmental stressors were listed with IG failure modes in the previous section of this chapter. The environmental stressors ultimately couple together to form a "stressor" function. A stressor function creates failure modes.

A Stressor Function

A fundamental stressor function is "delta-p" (Δp), which is the pressure difference between the IG air space and the atmosphere. "Delta-p", combined with the edge conditions created by the window frame cause normal and shearing stresses to act upon the sealants and spacer, and flexing stresses upon the glass lites. This function is dependent upon barometric pressure fluctuations (Δp_{bar}), IG air temperature fluctuations (ΔT), and the volume-pressure relationship (γ) for a particular IG unit.

The IG air space temperature fluctuations are a complicated function of atmospheric air temperature, window frame and sealant/spacer thermal characteristics, building air temperature, and incidental solar flux absorption.

Theoretical and analytic volume-pressure functions (γ) are developed in Chapter 6, Section 1, wherein we assumed the applicability of "thin-plate" theory to the IG unit. This theory states that the volume displacement of an IG unit (ΔV) is directly proportional to Δp:

$$\Delta V = \gamma(E_{seal}, w_{seal}, d_{seal}, E_{glass}, L, W, d_0, h) \bullet \Delta p \qquad (1)$$

The dependent variables of function γ are explained as follows:

E_{seal} = elastic modulus of the sealant, which changes with temperature, water activity, and accumulated UV damage.

w_{seal} = width of the sealant (parallel to the glass surface)

d_{seal} = thickness of the sealant

E_{glass} = elastic modulus of the glass lite

L = length of the glass lites

W = width of the glass lites

d_0 = "at rest" glass lite separation distance (Δp = 0)

h = thickness of the glass lites

It is shown that, to first order, the pressure difference function is a linear function of IG air space temperature fluctuations from the manufacturing point (T_0) and barometric pressure fluctuations from the manufacturing points (p_0).

$$\Delta p/p_0 = V_0/(V_0 + \gamma p_0) \bullet (\Delta T/T_0 - \Delta p_{bar}/p_0) \qquad (2)$$

where V_0 (LWd_0) is the "rest" volume of the IG. The volume-pressure function has a very complicated dependence upon the glass properties and geometry, the sealant/spacer properties and geometry, and the edge conditions determined by the window frame. Creating a reliable volume-pressure function will involve a combination of laboratory and field measurements and computational work.

Coupling to a failure mode

As a "zeroth-order" approximation, the normal stress on the primary sealant of an IG is proportional to the pressure difference function and the ratio of the glass lite surface area to the sealant surface area. This is described by Equation 3.

$$\sigma_{seal} = \Delta p\, A_{lite}/A_{seal} \qquad (3)$$

where

$$A_{lite} = LW$$

$$A_{seal} = 2(L+W)w_{seal}$$

Accumulating all of the equations together, the normal cohesive stress on the primary sealant is approximately

$$\sigma_{seal} = p_0V_0/(V_0 + \gamma p_0) \bullet (\Delta T/T_0 - \Delta p_{bar}/p_0) \bullet (LW/(2(L+W)w_{seal})) \qquad (4)$$

Other failure modes are rather more complicated and are left to be addressed in future work.

Proposed Application

Assume the volume-pressure function has been determined for a specific insulating glass unit and window sash. Assume we know the manufacturing pressure and temperatures. It now becomes possible to utilize a suitable weather database (such as from the National Weather Service [1]) and compute the time-dependent stresses which would be felt by the window in a particular environment. In the next section, the ability to transform defined environmental stressors, from information from the National Weather Service database, into analytical models which describe resulting physical stresses will be discussed.

References

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6. Physical Stress Models

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6.1 Internal Pressure of Insulating Glass Units as a Function of Environment

Objective

The lites of an insulating glass (IG) unit will bend and sealants will be strained in response to pressure differentials between the IG air mass and the external atmosphere. It is the objective of this section to realistically model these IG variations as functions of changes to barometric pressure and IG air temperature.

This model will provide insight into two significant parameters of IG performance: the pressure response, and the deflection response. These two parameters have been shown to be driving factors in several IG failure modes, including sealant cohesive normal stress and shear failure, as well as adhesive failure. Furthermore the effect of varying edge conditions, as a result of differing spacer system effective stiffness, will be developed to support understanding of this critical design variable.

<u>Model Development Step 1: Applying the Ideal Gas Law</u>

Assumptions

Over their useful lifetimes, properly functioning Insulating Glass (IG) units can be viewed as enclosing a relatively constant mass of gas. This gas, typically an air and argon mixture, can be viewed as following the ideal gas law:

$$\boldsymbol{pV = nRT} \qquad (1)$$

where **p** is the pressure, **V** is the volume, **n** is the moles of gas, **R** is the universal gas constant, and **T** is the temperature. Therefore, if the gas quantity is a constant, the ratio function of the variables (**pV/T**) is a constant:

$$pV/T = p_0V_0/T_0 \qquad (2)$$

where p_0, V_0, and T_0 are a reference state, typically chosen to be the values at the time of IG unit assembly. The reference volume, V_o, is the product of the surface area of the viewing area and the air gap distance between the glass panes, as shown below, where the length and width correspond to the glass viewing area.

$$V_0 = L\ W\ d_0 \qquad (3)$$

where

L = length of the glass lite (long lateral dimension)

W = width of the glass lite (shorter lateral dimension)

d_0 = equilibrium separation between the glass lites

Variable Definitions

To approach our goal of solving for the IG geometric changes based on barometric pressure and IG air temperature variations, let us define the variables p, V, and T in terms of the reference points and some “fluctuation” functions:

1. The internal pressure of the IG is alternatively written as

$$p = p_{bar} + \Delta p \qquad (4)$$

where Δp is the pressure difference between the IG and the atmosphere and p_{bar} is the barometric pressure. The latter can also be legitimately described as the manufacturing point plus a pressure variation from that point,

$$p_{bar} = p_0 + \Delta p_{bar} \quad (5)$$

and thus we can describe the internal gas pressure of the IG unit as a combination of the initial pressure state and two pressure fluctuation functions:

$$\boldsymbol{p = p_0 + \Delta p_{bar} + \Delta p} \quad (6)$$

2. We define the IG air temperature as

$$\boldsymbol{T = T_0 + \Delta T} \quad (7)$$

Let us also note that the fluctuation function **ΔT** does not equal the external air temperature variation but is rather a complicated (and unknown at this point) function of external air temperature variation, building air temperature, absorbed solar flux, and heat thermally conducted via the window frame.

3. We define the IG volume as

$$\boldsymbol{V = V_0 + \Delta V} \quad (8)$$

Relating all of the fluctuation functions into one equation

At this point we return to Equation 2 and substitute the reference and fluctuation parameters into the **pV/T** relationship to obtain

$$\boldsymbol{p_0 V_0 / T_0 = (p_0 + \Delta p_{bar} + \Delta p)(V_0 + \Delta V)/(T_0 + \Delta T)} \quad (9)$$

And with some modest rearrangement we arrive at a useful dimensionless equation which relates all of the fluctuation functions with each other:

$$1 + \Delta T/T_0 = (1 + \Delta p_{bar}/p_0 + \Delta p/p_0)(1 + \Delta V/ V_0) \quad (10)$$

In the next section we will apply thin plate theory and determine that this approximation yields the result that the volume fluctuation function (**ΔV**) is directly proportional to the pressure difference function (**Δp**)

$$\Delta V = \gamma \Delta p \quad (11)$$

where γ is a function of the flexural modulus and geometry of the glass lites as well as the structural properties of the sealant design (which are affected by water content, sealant temperature, and fatigue). If we substitute γ **Δp** for **ΔV** in equation (4) we can directly solve for **Δp** in the following quadratic equation:

$$(1 + \Delta p_{bar}/p_0 + \Delta p/p_0)(1 + \gamma\Delta p/V_0) - (1 + \Delta T/T_0) = 0 \quad (12)$$

We can solve the equation as a perturbation problem using the barometric and IG air temperature fluctuation functions as the perturbations (since they are small compared to the reference points). To first-order we get

$$\Delta p/p_0 = (\Delta T/T_0 - \Delta p_{bar}/p_0)\cdot V_0/(V_0 + \gamma p_0) \quad (13)$$

which is the pressure difference function utilized in Chapter 5, Sections 2 and 3, in which we propose its use to generate severity factors using the National Weather Service database. With the background in place, let us now proceed to develop a means of computing this pressure-volume relational function *γ*.

Model Development Step 2: Analytically Computing a Pressure-Volume Relational Function using Thin Plate theory and a Linear Stress Function on the Sealants.

It was desired to develop a pressure-volume approximation model with minimal mathematical complexity, so that the general relationships could be understandable from a design perspective. It was also desirable to develop an analytic procedure which would support minimal test validation. The model as shown below is currently awaiting validation from either FEA modeling or testing. This validation will occur during the proposed Phase 2 of the effort. At this point it is therefore only a hypothetical, unvalidated construct.

This step in the model development begins with consideration of elastic flat plate response as discussed in Roark [1]. The reference develops the midspan deflection of a flat plate as a function of the uniform pressure magnitude. The midspan deflection is determined for the end conditions of clamped edges as well as simply supported. The relationship for midspan deflection, Δz, can be expressed in terms of plate width, W; modulus, E; thickness, t; aspect ratio function, α; and change in pressure as follows:

$$\Delta z_{midspan} = \frac{\Delta P \cdot \alpha \cdot W^4}{E \cdot t^3} \qquad (14)$$

Where α is a function of edge constraint and aspect ratio and is defined as follows:

	Length/Width Ratio						
Edge Constraint	1	1.2	1.4	1.6	1.8	2	Infinite
Simply Supported	0.444	0.0616	0.077	0.0906	0.1017	0.111	0.1421
Clamped	0.0138	0.0188	0.0226	0.0251	0.0267	0.0277	0.0284

Table 6-1. Empirical Constants for Differing Edge Constraints

The midspan deflection of a flat plate subjected to uniform pressure is thus understood for the end conditions of full perimeter fixed and full perimeter simply supported. In order to develop the volume change response it is necessary to also have the deflection characterized as a function of location on the plate. It was desired to have a model with minimal parameters for this purpose.

When developing the model it is necessary to satisfy the boundary conditions. For the case of a simply supported plate, the boundary conditions include no reactive moment on the edge of the glass. Also, from symmetry, the deflection slope at the midpoint of the plate is zero. The boundary conditions for a simply supported plate are thus as follows:

At the edge of the plate — At the center

$$M = 0 \rightarrow \frac{d^2 z}{dx^2} = 0, \frac{d^2 z}{dy^2} = 0 \qquad \frac{dz}{dx} = 0, \frac{dz}{dy} = 0 \tag{15}$$

Since the plate is a solid structure, a further requirement is that the deflection of the plate be a continuous function, with no steps or discontinuities. In elastic stability theory [2,3], such distributed deflection response is often closely approximated by assuming cosine or sine distributions. When evaluated in this manner, a deflection response which satisfies the boundary conditions for the deflection response of a plate with respect to location can be expressed as follows, where x is the position along the length, y is the position along the width, and L is the length:

$$\Delta z_{normalized} = \left[\cos\left(\frac{\pi \cdot x}{L}\right)\right]\left[\cos\left(\frac{\pi \cdot y}{W}\right)\right] \tag{16}$$

When combining this distributed response with the midspan peak response identified by the Roark function, the pressure deflection relationship can be expressed as follows for a simply supported plate:

$$\Delta z = \Delta P \cdot \left[\frac{\alpha \cdot W^4}{E \cdot t^3}\right]\left[\cos\left(\frac{\pi \cdot x}{L}\right)\right] \cdot \left[\cos\left(\frac{\pi \cdot y}{W}\right)\right] \tag{17}$$

For the case of a fixed edge or clamped edge plate, the boundary conditions include no deflection slope on the edge of the glass. Also again, from symmetry, the deflection slope at the midpoint of the plate is zero. The boundary conditions for a fixed edge plate are thus as follows:

At the edge of the plate	At the center
$\frac{dz}{dx} = 0, \frac{dz}{dy} = 0$	$\frac{dz}{dx} = 0, \frac{dz}{dy} = 0$

$$\tag{18}$$

Again a continuous function is required. A sinusoidal model was thought to provide a reasonable approximation. The resulting normalized deflection model which satisfies the boundary conditions is shown below.

$$\Delta z = \left[1 + \cos\left(\frac{2 \cdot \pi \cdot x}{L}\right)\right]\left[1 + \cos\left(\frac{2 \cdot \pi \cdot y}{W}\right)\right] \tag{19}$$

The pressure deflection relationship, resulting from combining with the Roark midspan deflection relationship, can be expressed as follows for a clamped edge plate.

$$\Delta z = \Delta P \cdot \left[\frac{\alpha \cdot W^4}{4 \cdot E \cdot t^3}\right]\left[1 + \cos\left(\frac{2 \cdot \pi \cdot x}{L}\right)\right]\left[1 + \cos\left(\frac{2 \cdot \pi \cdot y}{W}\right)\right] \tag{20}$$

The following chart shows a comparison of the normalized deflections of the simply supported versus fixed edge flat plates.

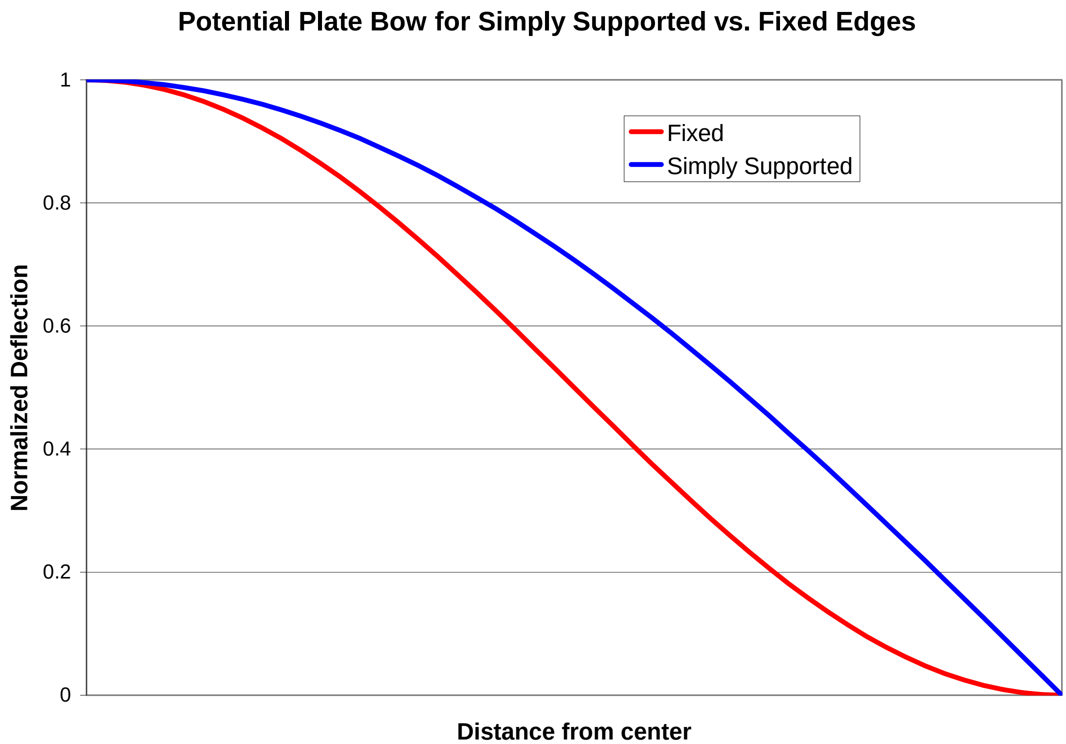

Figure 6-1. Plate Bow as a Function of Location and Edge Conditions

It is desirable to develop a general deflection relationship which captures both the fixed edge and simply supported conditions, which are the extreme end conditions. It is also desirable to have a function which captures degrees of stiffness between these two conditions. The degree of stiffness between the condition of simply supported and fixed edges can be represented by a parameter, c, which is proportional to the edge stiffness. A value of unity for c represents simply supported edges and a value of zero for c represents a fixed edge condition. By algebraic manipulation, the following general deflection relationship can be established. At the extremes of c=0 and c=1, the response is consistent with the fixed and simply supported models discussed previously.

The general deflection solution as a function of the edge condition becomes: (21)

$$\Delta z = \Delta P\left[\frac{\alpha \cdot W^4}{E \cdot t^3}\right]\left[\frac{1}{1+\cos\left(c\pi/2\right)}\right]^2\left[\cos\left(\frac{(2-c)\pi x}{L}\right)+\cos\left(\frac{\pi c}{2}\right)\right]\left[\cos\left(\frac{(2-c)\pi y}{W}\right)+\cos\left(\frac{\pi c}{2}\right)\right]$$

where: c= a measure of edge stiffness. c=0 corresponds to a fixed edge, c=1 corresponds to a simply supported edge.

To facilitate calculation, the α parameter in the above relationship can be expressed in terms of the plate dimensions and stiffness coefficient by performing a regression on the point values listed in Table 6-1. The resulting expression for the α parameter is as follows:

$$\alpha = (-.0077) - c(.01714) + \left[\frac{L}{W}\right](.0215) + c\left[\frac{L}{W}\right](.04774) \qquad (22)$$

The following chart shows the normalized deflection response of the general deflection model as a function of edge stiffness.

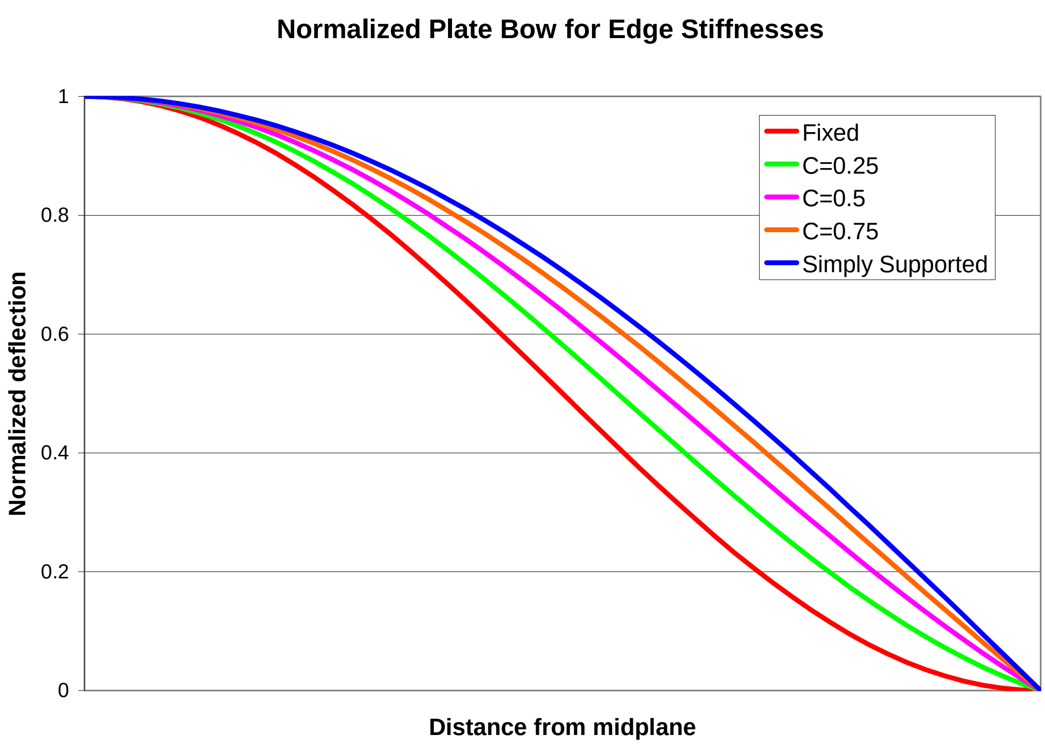

Figure 6-2. Normalized Plate Bow as a Function of Location and Edge Condition

The change in internal volume due to pressure flexure of the glass pane can be derived by integrating the deflection relationship equation. For a single pane of pressurized glass, the deflection relationship is integrated over x and y from the midplane for one quadrant of the plate. From symmetry the total volume change of the plate is four times the volume change in one quadrant of the plate. The resulting volume change as a function of pressure for one pressurized plate is given in Equation 23.

$$\Delta V = \Delta P\left[\frac{4\cdot\alpha\cdot W^4}{E\cdot t^3}\right]\left[\frac{1}{1+\cos\left(c\pi/2\right)}\right]^2 \cdot \left[\left(\frac{WL}{4}\right)\cos^2\left(\frac{\pi c}{2}\right)+\left(\frac{WL}{\pi(2-c)}\right)\cos\left(\frac{\pi c}{2}\right)\sin\left(\pi\left(1-c/2\right)\right)+\left(\frac{WL}{\pi^2(4-2c)}\right)\sin^2\left(\pi\left(1-c/2\right)\right)\right] \quad (23)$$

An insulating glass unit consists of two flat plates under pressurized loading deflection. The resulting change in volume due to pressure for an IG unit is therefore as follows.

$$\Delta V = \Delta P\left[\frac{8\cdot\alpha\cdot W^4}{E\cdot t^3}\right]\left[\frac{1}{1+\cos\left(c\pi/2\right)}\right]^2 \cdot \left[\left(\frac{WL}{4}\right)\cos^2\left(\frac{\pi c}{2}\right)+\left(\frac{WL}{\pi(2-c)}\right)\cos\left(\frac{\pi c}{2}\right)\sin\left(\pi\left(1-c/2\right)\right)+\left(\frac{WL}{\pi^2(4-2c)}\right)\sin^2\left(\pi\left(1-c/2\right)\right)\right] \quad (24)$$

The change in volume as a function of pressure relationship can then be used to solve the ideal gas relationship:

$$P_2 \cdot V_2 = \frac{T_2 \cdot P_1 \cdot V_1}{T_1} \quad (25)$$

Equation 25 can be rewritten in terms of the initial state and relative changes as follows.

$$\left[\Delta P + P_1\right]\cdot\left[\Delta V_{flexure} + \Delta V_{normalstress} + V_1\right] = \frac{T_2 \cdot P_1 \cdot V_1}{T_1} \quad (26)$$

Note in Equation 26 that it is not only necessary to understand the change in volume due to flexure, but it is also necessary to understand the effect due to normal stress deflection. Normal stress deflection is defined as a uniform movement of the plate over a deflection distance due purely to the normal stress on the sealant. If this volume change is quantified, the relationship in Equation 26 can then be solved.

The normal stress bulk movement contribution is developed by realizing that the bulk movement can be viewed as a strain occurring on the sealant. From the linear Hookean relationship of the sealant, the bulk normal stress deflection can then be stated as:

$$\Delta z_{normalstress} = \sigma_{sealant} \cdot \left[\frac{t_{sealant}}{E_{sealant}} \right] \qquad (27)$$

The stress in the sealant can be expressed by the total equivalent force divided by the exposed area of the sealant, where w is the width of the sealant:

$$\sigma_{sealant} = \frac{\Delta P \cdot L \cdot W}{w \cdot [2 \cdot L + 2 \cdot W]} \qquad (28)$$

Equation 27 and 28 can be combined to express the deflection in terms of sealant properties and the exposed glass pane geometry. The resulting volume change is determined by taking the product of the deflection and the glass pane area, as follows:

$$\Delta V_{normalstress} = \frac{\Delta P \cdot t \cdot L^2 \cdot W^2}{E \cdot w \cdot (2 \cdot L + 2 \cdot W)} \qquad (29)$$

All of the relationships have now been sufficiently established to allow solving both the pressure volume response and the ideal gas response of the IG unit. Equation 30 shows the final relationship which may be iteratively solved for the change in pressure response of the IG. The relationship of equation 24 will be used to model the flexure volume change as a function of delta P. The relationship of equation 29 will be used to model the normal stress volume change as a function of normal stress. All of the input volume changes are expressed in terms of the delta P, which enables the iterative solution.

(30)

$$\left[\Delta P + P_{assembly}\right] \cdot \left[\Delta V_{flexure} + \Delta V_{normalstress} + L \cdot W \cdot t_{airgap}\right] - \left[\frac{T_2 \cdot P_{assembly} \cdot L \cdot W \cdot t_{airgap}}{T_{assembly}}\right] = 0$$

The resulting model has been put into spreadsheet form for ease of implementation. As stated previously, model validation tests are yet to be performed to support its estimates. This validation will occur in Phase 2 of this activity.

References

1. Young, Warren C. (2002). Roark's Formulas for Stress and Strain. (7th Edition). New York: McGraw-Hill
2. Chajes, Alexander (1993). Principles of Structural Stability Theory (2nd Edition). Englewood Cliffs, New Jersey: Prentice Hall
3. Timoshenko & Goodier (1970). Theory of Elasticity (3rd Edition) New York: McGraw-Hill

6.2 Failure of an Insulating Glass Unit Due to Excessive Moisture Vapor Transmission under Ideal Conditions

Introduction

Predicting the time to failure of an insulated glass (IG) system under the conditions imposed in a typical building's natural environment is difficult. In an attempt to simplify the process of defining environmental stress, a starting point was selected. This starting point is defined as the set of conditions where environmental stress on an IG unit would be minimized. The primary purpose of the IG construction and sealants is to keep the interior of the IG unit clean and clear; dust, dirt, and moisture are typically the prime defect producing materials. A good sealant system's primary purpose is to control moisture while also excluding dust and dirt from the interior of the IG. To examine the ability of the sealant system to exclude moisture under ideal conditions involves placing a "perfectly" built IG in a room where the conditions are controlled precisely. When, after a period of time, the unit fails, the most likely failure would be the accumulation of excess moisture in the normally desiccated interior airspace. Only one type of IG spacer system will be considered initially: the dual-seal box spacer. The goal of this paper is to focus on the failure of an IG in the absence of natural environmental fluctuations. Other forces, failure types, and spacer systems will be studied in subsequent work and their effects on the IG system may be added in a superposition-type analysis.

An Ideal Environment Defined

It is expected that, with minimum environmental stress, an ideally constructed IG unit will fail due to slow accumulation of moisture in the internal airspace. Other potential failure causes are not being considered in this analysis and will be the subject of future analysis. To minimize the amount of stresses the IG will see in our theoretical room, and confine the failure analysis to excess moisture buildup in the interior airspace, the following conditions would be maintained:

A. Low light level. One contributing factor to degradation and failure of sealant systems, especially of polymer materials, is ultraviolet radiation from sunlight. Also, heat build due to solar irradiation will be excluded from this environment. A working level of incandescent lighting is assumed for observation and measurement purposes.

B. Constant temperature. The temperature would be set to the standard of either 20°C (68°F) or 25°C (77°F). Constant temperature will eliminate cyclical stresses associated with thermal contraction and expansion. This condition eliminates many of the degradation mechanisms involving a seal failure due to shear and tension stress arising from day-night and seasonal variations.

C. Constant relative humidity of 50% RH. To ensure a constant vapor pressure and thus a near constant vapor pressure stress across the spacer's boundary, the relative humidity is constant.

D. Constant pressure of 14.7psia, or a suitable pressure based on the elevation above sea level where the analysis/test takes place. Pressure control will eliminate cycling variations from changing barometric pressure. The IG units are assumed to be built at the temperature and pressure defined for this durability analysis to ensure that the partial air pressure difference across the IG seals would be zero.

These test conditions could be expanded to include additional scenarios in future work. When the basic characteristics of moisture diffusion through the sealant under minimum stress conditions are understood, then the true nature of moisture diffusion under added stress conditions may be more fully analyzed. Time-dependant cycling conditions would be included to match conditions seen in the built environment.

An IG Failure Due to Excessive Vapor in Airspace

Failure, in this analysis, is defined as the increase of the internal dew point to a specified limiting condition (typically either -20°F or -40°F). Normally, airspaces start at -90°F. The setting of the above conditions was done to eliminate some of the variable conditions that contribute to failures in actual IG unit installations. For example, no pressure differences imposed upon the exterior of the IG due to a changing barometer or wind load eliminates many cyclic stress failure mechanisms. The test conditions are chosen so that the major unit stress is the difference in vapor pressure across the sealant system, balanced by the ability of the internal desiccant to adsorb water vapor which diffuses through the seals. The IG unit would be constructed with a measured amount of desiccant typical of the amount used in normal production for the particular IG construction.

IG Airspace Composition

To keep this analysis simple, the dual-seal box spacer will be the only spacer system run through this analysis. The IG internal airspace considered for this paper contains normal atmospheric air composed of approximately 78% nitrogen, 21% oxygen, and 1% argon. The interior airspace is at a dew point of -90°F, or lower, from the initial desiccant fill. This corresponds to an internal vapor pressure of less than .0000526psia [Ref. 6]. The test atmosphere at 20°C (68°F) and 50% RH has a vapor pressure of 0.1695psia and at 25°C (77°F), with the same RH, has a vapor pressure of 0.2297psia. Water vapor, driven by this large pressure difference, diffuses through the sealant into the airspace. The goal of this paper is to predict the life of an IG in this environment, based upon the failure mechanism of water vapor infiltrating into the desiccated airspace. The water vapor is adsorbed by the desiccant up to the capacity of the desiccant at the failure dew point. Failure at -20°F corresponds to a vapor pressure of 0.00819 psia and failure at -40°F corresponds to a vapor pressure of 0.00274 psia. The time to failure will be computed using the MVTR of the sealant system and the moisture capacity of the desiccant.

A simplification can be made for this approximation by adding the time it takes the airspace to reach a -20°F dew point to the time it takes the desiccant to be ineffective based upon the mass transfer (diffusion) rate of water vapor coming into the airspace at an assumed constant rate. This simplification makes it easier to calculate the time to failure than plotting the time-dependant diffusion rates of both desiccant uptake and vapor transmission. A future paper could explore this possibility.

Spontaneous Failure versus Manufacturing Defects

The water vapor transmission path is assumed to be homogeneous throughout the sealant. If there is a manufacturing problem, there may be a breach of the sealant due to a bubble, void, or a localized area of poor adhesion. For the purposes of this paper, the IG unit is assumed to have perfect construction. It is also assumed that the desiccant has a minimum moisture content equivalent to -90°F or below. No alternate pathways between the desiccated airspace and the environment exist. The sealants are assumed to be in complete contact with each other, the spacer, and perfectly adhered to the glass. Since the purpose of this paper is to identify the time to failure due to excess water vapor transmission, defects are ignored and the unit is considered to be constructed perfectly. This will capture the spontaneous, equilibrium-driven mass transfer that would occur between the desiccated airspace and any environment that contains water vapor.

A Detail of the Spacer System Considered for this Paper

As previously mentioned, the dual-seal box spacer will be the only spacer system considered for this paper. This was chosen because it is commonly used in industry, and there is a great deal of information regarding this spacer system. The dual seal box spacer is a generalized design class, usually consisting of a primary sealant that keeps moisture out of the system, and a structural sealant to hold the system together, hence "dual-seal." The spacer itself is usually roll-formed aluminum or stainless steel bent into an enclosed shape for the desired geometry. The primary seal considered is a commercial PIB (polyisobutylene) compounded for IG applications. The secondary seal is a silicone based sealant. See Figure 6-3, below:

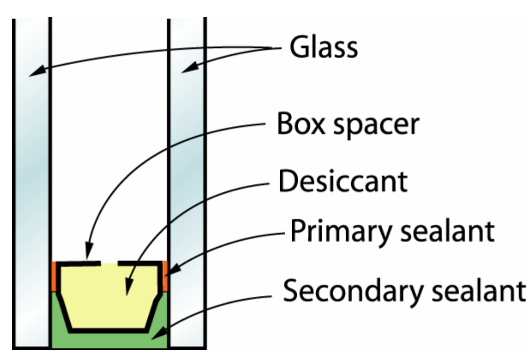

Figure 6-3. A Typical Dual-Seal Box Spacer System

The Vapor Transmission Mechanism

Vapor transmission occurs between two different masses of air with differing amounts of water vapor. Driven by a vapor pressure difference, the outside environment's moisture penetrates the desiccated airspace by the path of least resistance. Since one of the assumptions is that the IG unit is perfectly constructed, the water vapor must travel through the sealant or spacer material. For this examination, the glass and any metallic components will be considered impermeable. A survey of some of the common diffusion and mass transfer laws was conducted, as is shown in Appendix 6-1. The simplest way to calculate vapor transmission is to take advantage of material property tests. Most tests for vapor transmission, such as ASTM E96, report the value in grams of water per hundred square inches per day, at a specified thickness. The thickness must be specified, or the value obtained may not be correct. Typically, the thickness tested is comparable to the end-product's working thickness. The task is then to calculate how much area of transmission there is, the amount of water that the desiccant holds, and then compute the time directly from the vapor transmission rate. For a first approximation, an assumption is that there is no secondary sealant, or that it is much more permeable to water than the primary sealant, as is the case with most silicones. This method gives a reasonable time to failure for the purposes of this paper.

Definition of Control Volume

The definition of a control volume is a way of simplifying the system being considered by placing a boundary around a volume and analyzing what comes and what goes across the boundary. The control volume, or control space, will be defined as the internal space within the boundary established by the glass, spacer and sealants. The control boundary will assume a steady supply of 50% relative humidity air on the outer surface, while the inner surface encompasses the entire internal volume of the IG airspace including the desiccant. It is important to note that the complete time to failure will be the sum of two separate times during the mathematical simulation of vapor transfer, for simplicity and reasons mentioned above, namely to reduce complexity for this first approximation. In effect, the time and dew point temperature dependant nature of desiccant uptake is ignored for simplification. The next section will describe the process, and how it will be modeled.

The Control Volume Analysis

All of the above theory is pointless if certain assumptions are not made regarding the process occurring in the IG system. In this process, a supply of water vapor at a relatively high vapor pressure is surrounding a volume of air at a substantially lower vapor pressure. This pressure differential tends to force water vapor through the sealant system. The desiccant inside the airspace will adsorb the water vapor that penetrates the seal. The ability of the desiccant to adsorb water is shown by the isotherm curve for the desiccant. When the desiccant has adsorbed some amount of water vapor, its ability to adsorb more water vapor follows the isotherm curve [7].

As mentioned above, this simply means that the total time to failure is the sum of the time it takes the desiccant to reach saturation, or stop being effective, and the time it takes to change the IG airspace from a -90°F dew point to the critical -20°F dew point defined as a failure.

Theoretically, all that is needed for this analysis are the diffusion rates of vapor through the sealants, the sealant thickness and exposed surface area, the desiccant quantity and adsorption characteristics, and the volume of the interior airspace.

According to [3], there is only 6.5ppm (parts per million) of water in a typical airspace at 70°F and a -90°F dew point. For a 30" X 30" IG unit, that calculates out to about 3.10×10^{-5} grams of water (See Appendix 6-2). Since the failure point is when the unit gets to a -20°F dew point, it is useful to calculate the water in the airspace at that dew point: it turns out to be roughly 0.001907 grams of water. The calculation was done on a molar basis. For the full calculation, see Appendix 6-2. The failure rate is therefore dependant upon the size of the window, the area through which vapor can pass (spacer system), how much desiccant there is to adsorb the water, and the vapor transmission rate of the particular sealant in question. The above information is useful when attempting to plot various internal conditions.

Summary

Each spacer system has a unique set of polymer and/or metallic components. Using the vapor pressure and vapor transmission characteristics calculated according to the procedure above (and in Appendix 6-2) for a given unit size, in this case 30” X 30”, the overall estimated time to failure can be calculated for each system in a convenient spreadsheet, described below:

For A Dual-Seal Box Spacer:				
Width of Primary Sealant (in):	0.01		Total Vapor Trans. Area (in^2):	2.4
Distance from Primary/Secondary Sealant interface to Airspace (in):	0.156		Infiltration Rate (g water/day):	0.000372
Primary Sealant WVTR (g/100in^2/day):	0.0155		Water to Consume Desiccant (g):	11.7
Desiccant Loading (g/ft):	11.7		Desiccant Percent Fill:	1.000
Percent of Water take-up by Desiccant (%):	10.0		**Time in Years For Unit Failure:**	**86.2**

The calculation represents a best-case scenario for the life of the IG. It would fail in this time period if the only stress it saw was a vapor pressure difference across the sealant. The numbers above were calculated from published industry values. The width of the primary sealant is typical of a dual-seal box spacer, and represents the width of the orange area as seen in Figure 6-3. The distance from the primary sealant/secondary sealant interface to airspace is the effective path length for vapor transmission, assuming that the secondary sealant, usually a silicone, contributes very little to the blockage of vapor transmission. The primary sealant WVTR, or water vapor transmission rate, is a typical handbook value for polyisobutylene (PIB) rubber. This number could, in the future, be refined to reflect the WVTR at the exact thickness in this application by using ASTM E96. The desiccant loading is calculated by taking the area of the box spacer’s profile and multiplying by the density of the desiccant; this value was calculated assuming a spacer width of 0.432 inches (11mm). The percent water take-up by the desiccant is used as a typical value for a 3A desiccant that has been put into bead form, and further mixed with clay. The desiccant percent fill is simply how much desiccant was put into the box spacer versus the total volume enclosed by the spacer. These parameters can be changed. For example, if the spacer is 0.492 inches (12.5mm) wide, that changes the volume of air, the amount of desiccant, and the total weight of water in the airspace:

For A Dual-Seal Box Spacer:				
Distance from Box to Glass (in):	0.01		Total Vapor Trans. Area (in^2):	2.4
Distance from Primary/Secondary Sealant interface to Airspace (in):	0.156		Infiltration Rate (g water/day):	0.000372
Primary Sealant WVTR (g/100in^2/day):	0.0155		Water to Consume Desiccant (g):	13.8
Desiccant Loading (g/ft):	13.8		Desiccant Percent Fill:	1.000
Percent of Water take-up by Desiccant (%):	10.0		**Time in Years For Unit Failure:**	**101.6**

The time to failure increases due to the increased desiccant overcoming the relatively small airspace volume increase. Ideally, this is how long a unit would last in a controlled room; this also represents the maximum lifetime of a unit with this construction. With this tool, designs can be quickly compared to one another; however, this is considered an ideal model, and should be taken with precaution. These calculations assume that the time it takes the desiccant to load is much longer than the time it takes the dew point to change from -90°F to -20°F. Indeed, the time it takes the dew point to change is measured in hours, versus years for the time it takes the desiccant to load.

In the future, this model can be refined as more knowledge becomes available regarding the effects of moisture, pressure and temperature on the sealant system. Also, different sealant systems and different desiccants can be examined to see what their ideal maximum lifetimes would be.

Appendix 6-1: Diffusion and Mass Transfer Equations

The following fundamental equations of diffusion and mass transfer in general were examined during the course of writing this paper. Most of these equations contain cumbersome constants that are difficult to obtain empirically. In the next phase of this project, these equations, along with time-dependant differential equations involving desiccant uptake, will be employed to more accurately solve the problem above. This paper is considered an introduction to vapor transmission, and only an approximation will be generated by the above efforts. An understanding of these equations greatly facilitates the understanding of the driving forces involved in vapor transmission and diffusion.

For the permeable sealants and spacer materials, the main equations can derive from a molecular diffusive Arrhenius equation of the following form [1]:

$$Rate = c_o e^{(-Q/RT)}$$

In equation above, C_o is a constant, R is the gas constant (1.987cal/mol K), T is the absolute temperature (K), and Q is the activation energy (cal/mol). The activation energy is the energy required to cause an imperfection (in a crystal lattice) to move; this equation is commonly used to describe molecular movement through a crystalline matrix, such as carbon diffusing through iron in the steel-making process.

Fick's First Law of Diffusion is also commonly used to describe molecular movement through materials; the following equation is for a binary mixture of A and B [2]:

$$J_A^* = -CD_{AB} \nabla m_A x_A$$

In the above equation, J_A^* is the molar flux of species A (kmol/s·m^2), C is the total molar concentration of the mixture (kmol/m^3); D_{AB} is the binary diffusion coefficient or mass diffusivity. The Del operator (∇) defines the gradient of the species mass fraction m_A and species mole fraction x_A. The above equations are not very practical in day-to-day use, especially the molar Fick's First Law equation. A simplified version of Fick's First Law on an atomic level follows [1]:

$$J = -D \frac{\Delta c}{\Delta x}$$

This shows that the flux ***J*** (atoms/cm²·s), or movement of atoms, is proportional to the diffusion coefficient **D** multiplied by the concentration gradient Δ**c**/Δ**x** (atoms/cm³·cm). Fick's Second Law describes the gradient concentration of a substance as it passes through a permeable medium [1]:

$$\frac{dc}{dt} = D\left(\frac{d^2c}{dx^2}\right)$$

The above differential equation has a common solution [1]:

$$\frac{c_s - c_x}{c_s - c_0} = erf\left(\frac{x}{2\sqrt{Dt}}\right)$$

The above solution is based upon the initial conditions that occur during simple diffusion from one concentration to another through a permeable barrier. The term c_s is a constant concentration of the diffusing atoms at the surface, c_0 is the initial uniform concentration of diffusing atoms in the material, and c_x is the concentration of the diffusing atoms at a depth of **x** into the medium at time **t**. The Gaussian error function (***erf***) is used in this solution; tables exist to show the value of the error function for specified parameters. The above equations, or variations of them, will be useful when trying to determine the time to failure of the IG under the vapor transmission mechanism.

Appendix 6-2: Molar Calculation of the Mass of Water in a Desiccated Airspace

The first calculation is simply the interior airspace volume:

V= W*H*t

Where V is volume, W is the IG width, H is the IG height, and t is the air gap thickness. Using a condition-specific density of air as ρ=1.20kg/m^3 [5], the mass of air in the airspace can be calculated:

$m_{air} = \rho * V$

Then, the moles of air can be calculated with the standard molecular weight for air of M_a=28.97g/mol [4]:

mol air = m_{air} / M_a

With the moles of air the parts per million of water in air at specific dew point temperature is taken from Reference [3] and using the constant molecular weight of water as M_w=18.02g/mol, mass of water m_w in the air can be calculated:

m_w = mol air * (ppm H_20)/1e6 * M_w

The following is a sample calculation for a 76.2cm X 76.2cm (30" X 30") IG with an air gap of 1.1cm and inside dew point of -90°F, which has 6.5ppm of water according to Reference [3]:

V= 76.2*76.2*1.1 = 6387.1cm^3

m_{air} = 0.0012(g/cm3) * 6387.1cm^3 = 7.665g air

mol air= (7.665g) / (28.97g/mol) = 0.2646 mol air

m_w = .2646 mol * (6.5 ppm H_20)/1e6 * 18.02g/mol= 3.10e-5 g water

So there is 3.10e-5 grams of water in a 76.2cm X 76.2cm X 1.1cm IG that is at a dew point temperature of -90°F.

Below is a spreadsheet set up to calculate the changes in vapor in the airspace based upon unit size at different dew point temperatures:

Inputs:			**Outputs:**	
State 1: @ -90F Dew Point			**State 1: @ -90F Dew Point**	
Width of Unit (cm):	76.2		Volume of Interior Unit (cm^3):	6387.08
Height of Unit (cm):	76.2		Mass of Interior Air (g):	7.665
Air Gap (cm):	1.1		Moles of Dry Air:	0.2646
MW of Interior Air (g/mol):	28.97		Moles of Water in Air:	1.72E-06
MW of Water (g/mol):	18.02		Mass of Water in Airspace (g):	3.10E-05
Density of Air (kg/m^3):	1.20			
PPM of Water in Air:	6.5			

Inputs:			**Outputs:**	
State 2: @ -20F Dew Point			**State 2: @ -20F Dew Point**	
Width of Unit (cm):	76.2		Volume of Interior Unit (cm^3):	6387.08
Height of Unit (cm):	76.2		Mass of Interior Air (g):	7.665
Air Gap (cm):	1.1		Moles of Dry Air:	0.2646
MW of Interior Air (g/mol):	28.97		Moles of Water in Air:	1.06E-04
MW of Water (g/mol):	18.02		Mass of Water in Airspace (g):	1.91E-03
Density of Air (kg/m^3):	1.20			
PPM of Water in Air:	400			

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6.3 Modeling of Net Gas Loss from the IG Air-Space

Objective

A noticeable number of insulating glass (IG) units experience a net loss of gas content within their insulation space and thus enter a state of permanent concave bending, or "collapse" of the glass lites [1], independent of barometric pressure and temperature fluctuations. Empirically, it is known that inert-gas-filled IG units exchange gases with the atmosphere in such a manner that the gas (primarily argon) escapes from the IG space faster than oxygen or nitrogen gas can replace it.

Our objective is to establish appropriate differential equations to model the permeation mechanisms, as well as a simple algorithm to solve the differential equations.

Miscellaneous Information

DIN Standard 52293 limits argon loss to less than 1% per year; also, initial argon fills must exceed 90%. There is no corresponding American standard.

Manufacturer-specific field return data and test results do not appear to be publicly available information.

A.H. Elmahdy and Said A.Yusuf published an argon-retention durability study at an ASHRAE symposium in 1995 where they reported the results of running weathering cycles to simulate five years of field exposure [2]. Their data appears to indicate that there are variations in argon retention ability as either a function of sealant design or workmanship. This work remains uncited, although it is clearly an excellent review and experimental paper.

A. W. Czanderna [3], in a summary report to the National Renewable Energy Laboratory, has recommended the cessation of inert-gas fills: "The use of argon in an IGU as an energy-saving benefit when coupled with the known failure mechanism is seriously questioned….."

Miscellaneous technical briefings and reports concerning inert-gas fills have been filed with the IGMAC, SIGMA and other organizations since the 1980's.

Pragmatic Assumptions to Modeling

(1) Since gas pressures are well below 37 atmospheres and temperatures are much greater and 133 Kelvin, we make the reasonable assumption that the ideal gas law is applicable, and accurately describes the gas quantity (n) within the IG unit:

$$pV = nRT \qquad (1)$$

where

p = total gas pressure within the IG
V = volume of the IG
R = gas constant (8.31 J/mol-K)
T = absolute temperature (Kelvin)

The total gas quantity is the sum of the constituent gases which are nearly all argon atoms, nitrogen molecules, and oxygen molecules; we will ignore lesser atmospheric constituents (e.g. carbon dioxide, krypton)

$$n = n_{Ar} + n_{N2} + n_{O2} \qquad (2)$$

The internal gas pressure is a simple sum of the partial gas pressures (Dalton's Law)

$$p = p_{ar} + p_{n2} + p_{o2} \qquad (3)$$

Therefore each gas has its own ideal gas law equation

$$p_{ar}V = n_{ar}RT \qquad (4)$$
$$p_{n2}V = n_{n2}RT$$
$$p_{o2}V = n_{o2}RT$$

(2) We will assume that water uptake is accounted for by the desiccant design. If it is not, a catastrophic MVTR failure has occurred which will obscure all other concerns.

(3) The desiccant absorbs water vapor and essentially no nitrogen, oxygen and argon.

(4) The thin plate approximation is valid – the volume change of the IG unit space is directly proportional to the pressure differential.

(5) Sealants are isotropic in their material properties (modulus, permeation, etc)

Partial-Pressure Permeation Gas-Exchange Model

Permeation rates through a barrier (sealant) tend to vary with the type of gas. Typically, argon will travel through a polymer sealant at a higher rate than oxygen or nitrogen at temperatures tolerable to humans.

Gas molecules traverse a barrier when a pressure gradient exists across the barrier. The flow of gas "X" through a barrier is directly proportional to the pressure difference across the barrier:

$$dn_x/dt = -P_x \cdot (A/l) \cdot \Delta p_x \qquad (5)$$

where

$\boldsymbol{t}$ = *time*

$\boldsymbol{n_x}$ = *a specified quantity of gas "X" (e.g. moles of argon)*

$\boldsymbol{P_x}$ = *permeation "coefficient" for gas "X" through the barrier*

$\boldsymbol{A}$ = *exposed surface area of barrier*

$\boldsymbol{l}$ = *path length through the barrier*

$\Delta \boldsymbol{p_x}$ = *pressure gradient across the barrier*

While permeation through the polymeric sealants cannot be avoided, in principle the gas exchanges should occur over a time scale of decades, at the earliest.

However, the process can occur in a time scale of months or years because the IG unit is a *system*, an assembled group of components, vulnerable to attack at all interfaces. High system gas permeation can result from numerous possibilities, among them being poor initial workmanship, poor sealant choice, accumulated cracks in the sealant as it fatigues, and cracks in the adhesion layer between the glass surface and sealant due to fatigue.

Computational approach

We propose the use of Euler's rule combined with the partial ideal gas laws to compute the moles and pressures within the IG unit as a function of time.

Given the differential equation for the molar flow rate (dn/dt) of each gas

$$dn_{ar}/dt = -f_{ar}\,(p_{ar}, p_{n2}, p_{o2}) \qquad (6)$$
$$dn_{n2}/dt = -f_{n2}(p_{ar}, p_{n2}, p_{o2})$$
$$dn_{02}/dt = -f_{o2}(p_{ar}, p_{n2}, p_{o2})$$

where we have already shown that $\boldsymbol{f_x}$ is a function of the various partial pressures and other parameters, the type of gas loss, the specific gas, and the initial conditions.

We apply the Euler approximation as follows:

$$n_{ar}(t+\delta t) = n_{ar}(t) - f_{ar}\,(p_{ar},p_{n2},p_{o2})\,\delta t \qquad (7)$$

$$n_{n2}(t+\delta t) = n_{n2}(t) - f_{n2}(p_{ar},p_{n2},p_{o2})\,\delta t$$

$$n_{o2}(t+\delta t) = n_{o2}(t) - f_{o2}(p_{ar},p_{n2},p_{o2})\,\delta t$$

where δt is a small time increment. So the total change in gas quantity within the IG space is given by

$$\delta n = n(t+\delta t) - n(t) \qquad (8)$$

or

$$\delta nRT = (p+\delta p)(V+\delta V) - pV \qquad (9)$$

which can be solved exactly for the incremental volume change (δV) since we have assumed the validity of the thin plate approximation:

$$\delta V = \gamma \delta p \qquad (10)$$

Solving the resultant quadratic equation is an exercise left to the reader:

$$\delta V^2 + (V + \gamma p)\ \delta V - \delta n\ \gamma RT = 0 \qquad (11)$$

With δV known, we may now solve exactly for the inner partial pressure changes of the gas components which correspond to the gas quantity changes:

$$p_{ar}(t+\delta t) = n_{ar}(t+\delta t)RT/(V + \delta V)$$

$$p_{n2}(t+\delta t) = n_{n2}(t+\delta t)RT/(V + \delta V) \qquad (12)$$

$$p_{o2}(t+\delta t) = n_{o2}(t+\delta t)RT/(V + \delta V)$$

Continue to solve iteratively and one can generate gas quantity and pressure curves as a function of time or parametrically with each other.

A Proposed Testing Methodology

Insulating glass units are tested in environmental-cycling chambers. Therefore we will structure a testing methodology around this fact. Let us start with the ideal gas law, slightly rearranged:

$$pV/nT = R = 8.31 \text{ Joules/mole-Kelvin} \qquad (13)$$

We may now structure a very simple mathematical arrangement:

$$p_0V_0/n_0T_0 = [(p_0 + \Delta p + \Delta p_{bar})(V_0 + \Delta V)]/[(n_0 + \Delta n)(T_0 + \Delta T)] \qquad (14)$$

This is easily rearranged to:

$$(1 + \Delta n/n_0)(1 + \Delta T/T_0) = (1 + \Delta p_{bar}/p_0 + \Delta p/p_0)(1 + \Delta V/V_0) \qquad (15)$$

where

Δn is the change in the total gas content relative to the reference, n_0

ΔT is the change in the IG air temperature relative to the reference, T_0

Δp is the change in the IG air pressure relative to the reference, p_0

ΔV is the change in the IG air space volume relative to the reference, V_0.

Δp_{bar} is the fluctuation in the barometric pressure relative to reference, p_0.

The relationship between the IG volume changes and its air temperature and pressure fluctuations will be pre-measured. The initial gas fill of the IG unit will be pre-measured as well. The IG unit will be equipped with a sensor to measure the internal gas temperature and a differential pressure sensor to record Δp. For added useful information, a pair of proximity sensors will be added on the outer surfaces of the glass panes to provide center-to-center information. Finally, the barometric pressure will be recorded at all times.

The IG unit will stay in the environmental-cycling chamber for the duration of the test. With the continuous stream of pressure, temperature and glass pane separation information, the internal gas content can be computed real-time for the duration of the test. The predictions of the permeation model can be applied to match the empirical data, with the end result being knowledge of how the IG system incurs changes in its permeation characteristics over time.

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7. Top Level Durability Assessment

Richard Hage, Michael Eastep

7.1 Approach Template

A methodology is presented which will result in top level system durability assessments for specific products which have field service data. The methodology involves capturing understanding of the system using Failure Modes and Effects Analysis, developing a system model consistent with available failure code information, capturing time to failure information, and mathematically combining the failure mode response to determined system durability.

The purpose of this paper is to discuss a methodology which can be employed to provide a reliability assessment of an existing product which has field service data. The specific implementation of this methodology will be to fulfill a task of Phase I of the DOE funded project, "An Insulating Glass Knowledge Base". This methodology provides a top level reliability assessment as it assesses the durability of specific defined product directly from observed field failures. It is contrary to a bottom up approach, which would involve capturing underlying failure mechanisms, inputting variation into the mechanisms, and then arriving at overall product durability estimates.

The approach has the advantage of only requiring field service data of a specific product. It has the disadvantage that the durability projections are only valid for the specific product design considered. The effect of design variations and environmental variations on product durability can only be captured at a macro level.

The methodology developed towards the end result of capturing and quantifying such failure events for new products can be outlined as follows:

1. Statement of the problem
2. Failure Modes and Effects Analysis of the proposed product
3. Development of system model which incorporates the individual failure modes
4. Review of Field Service Data for resolution
5. Correlation of system model failure modes with field service failure codes
6. Determination of relevant design attribute variations
7. Capture of time to failure data at appropriate failure code and geographical resolution for all relevant design attribute variations
8. Fit probabilistic distributions to the time to fail data at the failure mode level
9. Combine the failure mode distributions into the system model
10. State the system level reliability for the defined warranty period, as a function of environment and design attributes

The first step is proper statement of the problem. This involves determination of which core product offering to assess and which of its design variants to consider. It also involves determining which geographic region to consider. What constitutes product must be defined. Finally the time periods of interest must be evaluated.

The Failure Modes and Effects Analysis (FMEA) must be performed with a diverse group which includes all relevant product experts [1]. The team should at a minimum include representatives of quality, design, service, production, and marketing. The FMEA results in a documented reference of the team's current best understanding of the system's potential failure modes. The causes and effects of the failure modes will be identified, as will the measures available for detecting the required metric. Severity, frequency of occurrence, and likelihood of detection will be determined. Risk priority numbers, based on severity, frequency, and detection likelihood will provide clarity as to how much resolution must be captured for the failure modes in the subsequent reliability development. The FMEA provides the template from which a system model can be developed. It also captures insight into which design attributes and environmental parameters affect system durability.

The system model must then be constructed. It is a representation of how failure modes interact to result in product failure. The system model will typically take the form of a block diagram or an event tree. System block diagrams, such as shown in Figure 7-1, are used when there is no interaction between failure modes [2]. System block diagrams can represent series systems, redundant systems, or a combination of both. Series systems are those where a failure of any subsystem will result in total system failure. Redundant systems have a great reliability advantage over series systems. In practice, however, redundant systems are often impractical to achieve due to cost and design constraints. Systems that can be modeled as series, redundant, or combination system block diagrams are relatively straightforward for analysis purposes, as they will result in an exact mathematical solution.

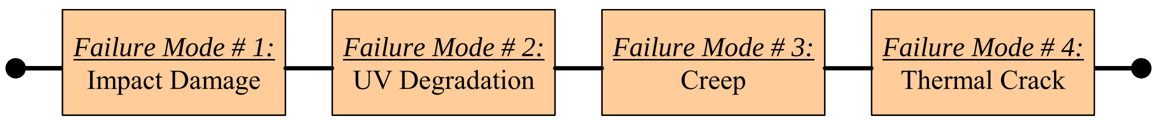

Figure 7-1. A Series System Block Diagram

Event tree diagrams are used to represent systems with complexity beyond that which can be captured with block diagrams [2]. In particular, they are necessary when there is either time dependence or physical interaction among the failure modes. The diagram generally shows the chains of events which result in individual failure modes. Event tree analysis models in general can not be solved with a direct mathematical solution. Rather, simulation methods such as Monte Carlo simulation must be used.

The field service data for the product must then be reviewed. The quantity and quality of the field service data will dictate the resolution of the assessment with respect to each of the following parameters:

- Geographic resolution
- Time to failure resolution
- Failure code resolution
- Design attribute resolution

In addition, the field data must include information on the sales volume within the defined geographical regions. The sales information is necessary as only a fraction of the product fails during its warrantable lifetime. The sales data is necessary so that the reliability statements can account for the unfailed products. It is desirable, although not necessary, that the field service data indicate the age of the product at failure. If the time to failure data is available, distributions such as the Weibull can be used, which capture the shape of the failure distribution. The shape of the distribution will indicate whether the failures are governed by infant mortality, random, or wear out failures. Capturing the shape of the distribution is important as it affects the magnitude of future failure projections. If time to failure data is not available, it is necessary to assume a constant failure rate for the failure mode, which may result in non-conservative failure projections. Finally, the quantity of both sales and failure data within the areas of geographical resolution will dictate the accuracy of the most likely durability estimates of the data. The quantity of data will also dictate the span of confidence intervals for the projections.

Ideally, the field service data will contain failure code information consistent with the failure modes included in the system block diagram. If this is not the case, the course of action is dictated by whether the failure codes are more coarse than the failure modes, or whether they are more detailed. If they are more coarse, the system block diagram must be simplified to be consistent with the reported failure codes. This is accomplished by grouping the failure modes into the groupings consistent with the failure codes. If the failure codes are to a greater level of detail than the failure modes, the failure code data must be grouped into a coarser grouping consistent with the failure modes. It is also possible that a combination of the two situations is present. In this case, the failure codes must be aggregated for some failure modes and the failure modes aggregated to match other failure codes. The resolution of the time to failure data must be updated to include the failure code aggregation and the system block diagram must be updated to accommodate the aggregated failure modes.

It is then necessary to hypothesize which design attribute variations are relevant for the assessment. The design attributes which are thought to have an impact on the product's durability should be chosen. The design attributes are chosen based on the qualitative or quantitative physical understanding of which factors affect the magnitudes of physical stresses which the IG sees during exposure to its environment. Examples of potential design attributes of interest with respect to IG durability are the color of the window frame, and the length and width dimensions of the IG. The color of the window frame is relevant as solar absorption of the window frame dictates the temperature and thus thermal expansion response of the frame. The thermal expansion of the window frame may then result in a deleterious effect on the IG. The result may be glass fracture or spacer system failure. The length and width dimensions are relevant as they dictate both the thermal state and the pressure state within the IG interior. Everything else held constant, windows of greater dimensions would tend to flex more than would windows of smaller dimensions, thus affecting both the pressure state and the edge flexure conditions. Also the larger windows would have proportionately greater static weight, which may affect spacer durability. When assessing which design attributes to consider, it is necessary to choose a list which is consistent with the resolution of the failure data. The categorization of the data is then complete. The time to failure data is then presented for each combination of the following parameters:

- Geographical/Environmental region
- Design attribute 1
- Design attribute 2

…

- Design attribute N
- Failure code groupings

The sales data for each combination of the above groupings are also tabulated. The time to failure data is constructed consistent with the resolution of the field service time to failure data. The number of failures within each time increment is captured. The quantity of product that has not failed is captured by subtracting the sum of failures from the total sales quantity.

The time to failure data for each combination of the above parameters is then fit to appropriate reliability distributions. The procedure for properly fitting a distribution involves the following three steps:

- Assume a distribution
- Calculate the distribution parameters
- Verify the proper fit of the distribution

The initially assumed distribution is generally determined by the failure mode considered. Three commonly used distributions are the Exponential, the Lognormal, and the Weibull. The exponential is generally used for systems with several components which all experience independent failures [3]. For this reason it is often used for describing the behavior of electronics systems, such as computer motherboards. It has the characteristics of a constant failure rate. If time to failure data is not available, this distribution is assumed, as there is no evidence to negate the constant failure rate hypothesis.

The Lognormal distribution is used often for failure mechanisms which have significant early failure due to manufacturing issues, but then fail less frequently as their time exposure increases (3). For this reason it is often used to describe bearing failures and turbine failures, as they represent cases where manufacturing defects often manifest themselves early.

The most commonly used distribution is the Weibull, shown in equation 1 [4]. The Weibull distribution is often used as it is flexible enough to capture a wide variety of failure distribution forms. The Weibull distribution for cumulative failures is described in Equation 1. Its parameters include a shape parameter, β, and a characteristic life term, θ. The shape parameter provides the Weibull with its substantial flexibility in modeling varying distributions. A shape parameter of 1.0 allows the distribution to model random failures. A shape parameter of less than 1.0 allows the distribution to model infant mortality failures. These early failures are often seen when initial manufacturing defects progress to failure early in a product's life. A shape parameter of greater than 1.0 allows the distribution to model wear out failures, such as would be the case for cumulative fatigue failures.

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\theta} \right)^{\beta} \right] \qquad (1)$$

Once the distribution has been chosen, it is fit to the data. This is accomplished by mathematically valid statistical techniques, which generally use minimal error fits. The distribution is fit by finding the values of its parameters which minimize the fit error. The fit distribution must then be validated as properly reflecting the data. This is accomplished by comparing the observed data to that predicted with the fit distribution. If the error is within an acceptable range, the distribution is found to be the proper choice. If the error is greater than the allowed error band, the selection of distribution must be reassessed. Two common methods for accomplishing this "goodness of fit" assessment are the Kolomogorov-Smirnoff technique and the Chi-square technique [3].

At this point, the reliability projections for the individual failure modes are incorporated into the system model. The failure mode reliability projections are thus mathematically joined and the overall system reliability projections can be determined. If a system block diagram was used as the construct, the reliability projections can be determined directly. If an event tree diagram was used, Monte Carlo simulation methods will be employed to determine the system reliability.

The system reliability is thus set up to project the product's reliability over the time period of interest. To evaluate the cumulative failures expected during a product's warrantable lifetime, all that is required is to set the time parameter of the probability distributions to match that of the warrantable lifetime. The system reliability can thus be quantified for a warranty lifetime, as can the cumulative expected failures. The failure rate over a defined time interval can also be assessed.

The output of this methodology will be top level durability assessments. For the specific product evaluated, the effect on durability of environmental region and design parameters can be assessed. It is possible that the effect of individual environmental quantities can be assessed, if the environmental regions are chosen to a sufficient level of resolution.

By employing this methodology for a variety of products, the relative reliability of differing products can also be assessed. If there are consistencies in the design attributes of various products, direct comparisons of different products can be provided.

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7.2 Implementation of Methodology for a Box Spacer System

The methodology outlined in the previous section was specifically applied towards an assessment of the box spacer system. The data was provided as a contribution to support the development of the Insulating Glass Knowledge Base.

The objective of the effort was to first to provide an assessment of product reliability for fenestration systems which use a box spacer design. Secondly, the reliability prediction for variations of the window system would be used to make general statements of the impact on system reliability of both design attributes and environment attributes.

The reliability statements will be made with respect to the likelihood of a customer reporting a failed problem. This was thought to most accurately capture the threshold of failure from the customer's perspective. It also allows the predictions to be tied to reported failures in a field service database. Information can be extrapolated from the reported failures to support failure projections in future years. This representation may be somewhat simplistic in that it assumes the customer's sensitivities to product failures do not increase or decrease over time. The phase II effort will consider the impact of changes in customer sensitivity over time, but such an undertaking was beyond the scope and resolution of the initial phase I projections.

The Failure Modes and Effects template for the box spacer design class was referenced during the development. To determine the system model the resolution of the field service data was weighed against the resolution of the FMEA. The resulting system model was a block diagram series system with the following failure modes:

- Condensation failure
- Collapse failure
- Glass failure

It should be noted that the estimates based on these failure modes are dependent on the validity of the field service data records. There is opportunity for miscoding as there is some judgment required. Particularly, the service technician uses his best judgment to properly match the failure codes with the observed failure. For some codes the proper failure code match is more obvious than others. For collapsed failures, the failure is often noted when a condensation ring is noticed. Because of this, even though the actual failure is collapse, the failure code chosen is condensation. Such coding errors may contribute significantly to observed differences in the data.

It was desirable to capture the effect of environmental parameters on system reliability. To this end, the resolution of the data in terms of the defined region to which it was sold and the defined region from which it failed was considered. Another factor in determining the resolution was the number of sales in a defined region and the number of failures in the region. All of these factors resulted in an environmental/geographical resolution of four areas in the continental U.S. which were as follows. There were not sufficient sales and failures in all of these regions to make statements about all variations. The environmental regions and their geographic location are as follows:

- Low Temperature, Low Precipitation Region
  Northern west non-coastal states

- Low Temperature, High Precipitation Region
  Northern coastal states, Great Lakes states

- High Temperature, Low Precipitation Region
  Arid southwest states

- High Temperature, High Precipitation Region
  Southern coastal states

It was also desired to make statements of the effect of design attributes on system reliability. As for the environmental attributes, this resolution was dictated by the sales and field service data. It was desired to understand the dimension effect, the effect of glass thickness, the effect of the coating, and the effect of different sash and frame systems. From the data some information was derived regarding the dimensions, the glass thickness and differing sash and frame systems. To make general statements it would be desirable that the effect of each parameter be assessed while holding all of the other parameters constant. Ideally all variations could be assessed within the framework of a Design of Experiments approach. Unfortunately, though, the geometry variations with frame system product lines and limitations of sales and failure quantities of some variations made a classical Design of Experiments approach impossible. Lacking complete information for a Design of Experiments, some insight was sought by looking at trends across direct comparisons. Although the resulting statements will not be conclusive, they may provide some insight into development of hypotheses regarding system failure.

The screened data was then assessed using parameter fit software. The data was found to be adequately fit to Weibull distributions. The data fit showed that each failure mode's failure rate closely approximated a constant failure rate. These underlying failure mode distributions were combined into a total system model

The system reliability projections, and resulting cumulative failure projections were stated over typical lengths of warrantable periods. The cumulative failure projections were stated on time basis for product age up to 20 years. In addition to the time projection curves, two specific time periods were considered for evaluation of failure mode effect. The specific times considered were 5 years and 10 years. These two time intervals were evaluated because many warranty programs cover a 10 year time interval. A five year interval was considered because it is possible that the owner of a new home will have different expectations of IG performance relative to that of a second or third owner of a home. Initial owners may have high expectations, while following owners will expect some problems with the older house and its older windows.
The system reliability projections are presented in the following section, together with analysis of perceived trends.

7.3 Box Spacer System Assessment

Three general product lines were considered in this effort. They were a casement product (C), a double hung product (DH-1), and a double hung product which is differentiated from the alternative product (DH-2). Several dimensions of each product line were considered. Within the casement line, variation of glass thickness was also considered. The definition of the product considered is shown in Table 7-1.

Product	Approximate Dimensions		
	Height	Width	Glass Thickness
Casement (C)	43"	24"	2 mm
	55"	24"	2 mm
	67"	24"	2 mm
	67"	32"	3mm
Double Hung-1 (DH-1)	20"	28"	2 mm
	32"	24"	2 mm
	32"	28"	2 mm
Double Hung-2 (DH-2)	27"	24"	2 mm
	27"	28"	2 mm
	31"	24"	2 mm

Table 7-1. Product variations considered in the Top Level Assessment

The initial investigation is to determine if general statements can be made concerning the relative frequency of the failure modes. Figures 7-2 through 7-4 are referenced in this discussion. All of the figures show the projected response in the low temperature, high precipitation environmental region. This region was chosen as it contains the highest volume of product and thus will allow the greatest amount of resolution. The product dimensions chosen from each product line represent high product volume in the region. Figure 7-2 shows the failure mode response of the casement product of 43"x24" dimensions. Figure 7-3 shows the failure mode response of DH-2 double hung product of 31"x24" dimensions. Figure 7-4 shows the failure mode response of DH-1 double hung product of 32"x24" dimensions.

From each of the figures it is clear that the reported collapsed failures are significantly lower than reports of condensation or glass fracture. In all cases the collapsed failures have a frequency of reporting of an order of magnitude or less compared to condensation or glass failures. The dominant failure between condensation and glass fracture is not always consistent across product lines, however. For the casement product, condensation failures are reported at greater than twice the frequency of glass failures. For the DH-2 double hung product, the condensation failures are reported at a rate nearing four times that of glass failures. For the DH-1 double hung product, the reported rate of glass failures is slightly greater than that of condensation. Whether the variation in condensation versus glass failure frequencies is attributable to design differences, process variations, or measurement variation is unclear.

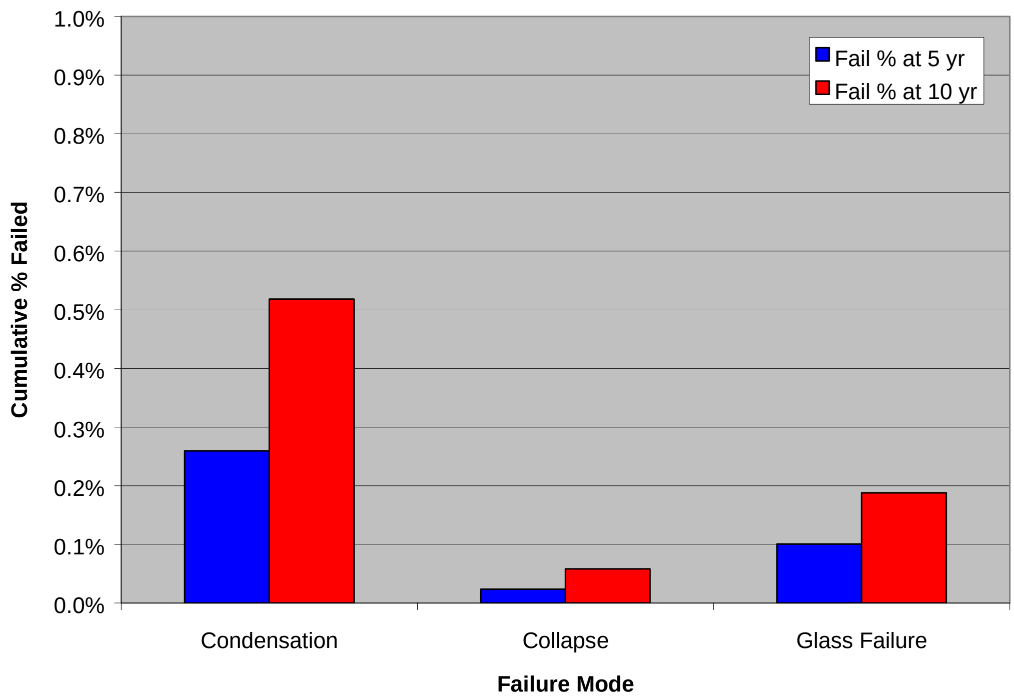

Figure 7-2. 43"x24" Casement Failure Mode Cumulative Failure %

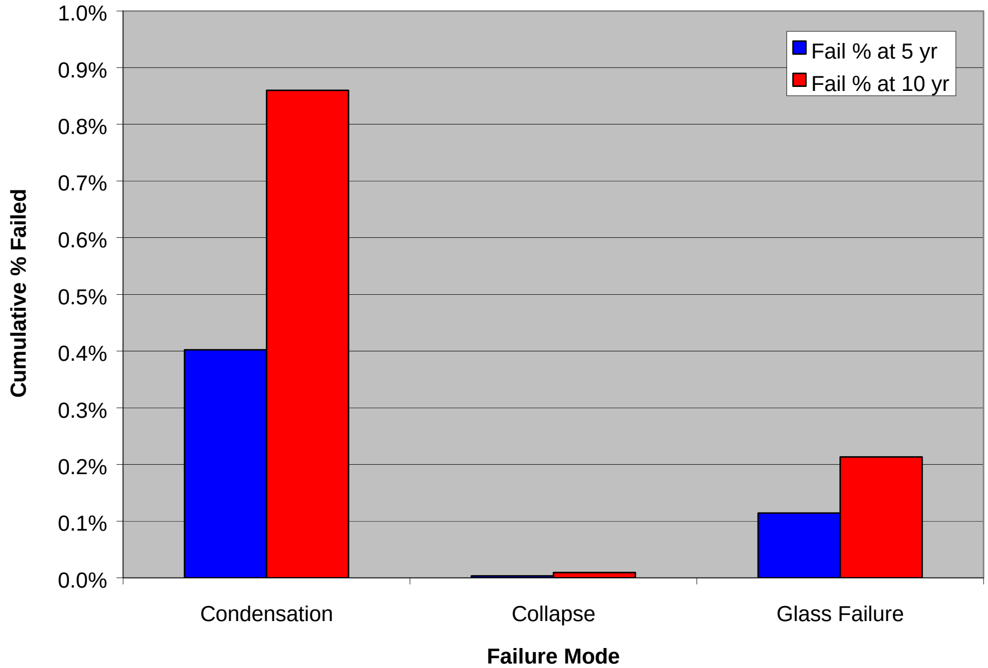

Figure 7-3. 31”x24” DH-2 Failure Mode Cumulative Failure %

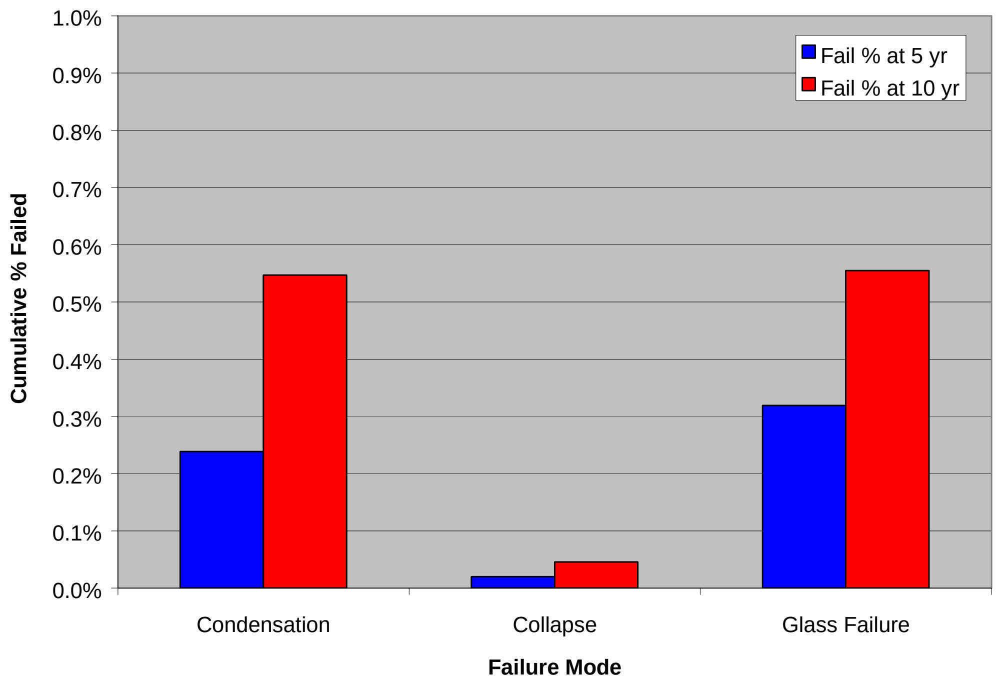

Figure 7-4. 32”x24” DH-1 Failure Mode Cumulative Failure %

The effect of product dimensions on product reliability is now considered. The effect of variations in dimensions within each product line will be considered. Figures 7-5, 7-7, and 7-9 show the projected product reliability for the variations in dimension. Figures 7-6, 7-8, and 7-10 show the relative contributions of failure modes to the projected product failures.

First, consider the dimensional effects shown for the casement product, in Figures 7-5 and 7-6. For each of the failure modes and for the overall system, the projected cumulative failures increase as the product area increases. This makes intuitive sense as a greater area, means a greater amount of crack initiation sites for glass failure. Also greater dimensions result in greater flexure of the window and thus more opportunity for collapse or cyclic dishing. Greater area also means more perimeter area for condensation to occur.

The dimensional effects for the double hung product, DH-2, are shown in Figures 7-7 and 7-8. The dimensional variation considered in this product cover a narrower and different range than for the previous product line. Therefore the comparisons for the product lines will only be relative within them, and can not be extrapolated across product lines. For this product line, also it is seen that as the area increases the project system failures increase. The driving failure mode in this case is condensation, as it increases significantly more than the other failure modes. Reported condensation failure increases 90% compared to 37% for glass failure. Collapsed failures stay approximately constant. There is a significant increase in condensation and collapse failures as the unit dimensions go from 31"x24" to 27"x28". This dimension change is a slight increase in area, a significant difference in aspect ratio, and an increase in the width dimension. It is unclear which of these changes are driving the increased reported condensation and collapse failures.

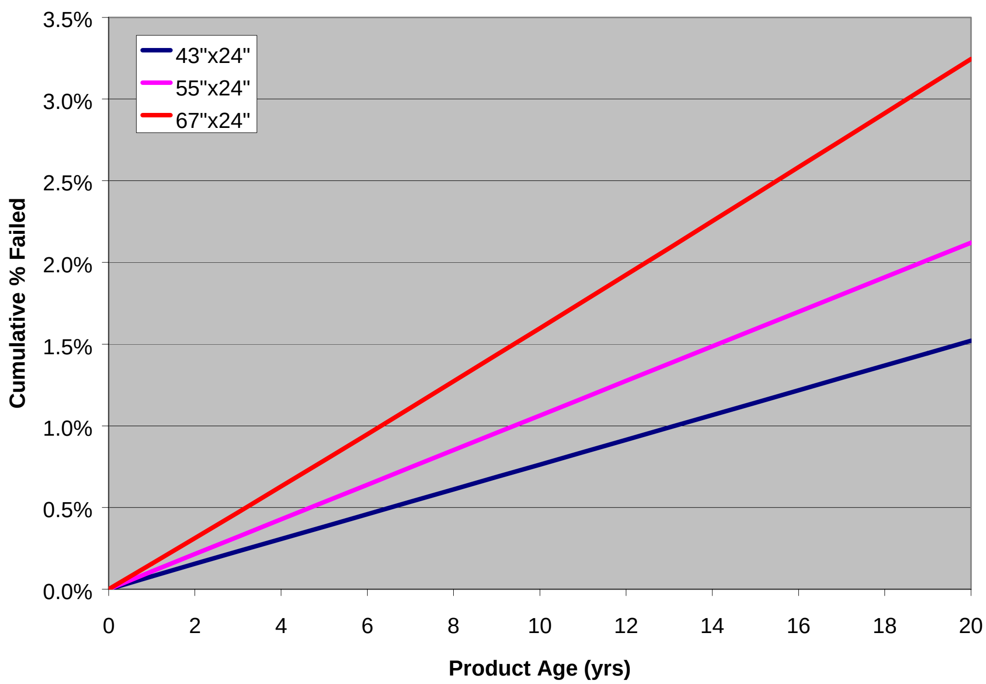

Figure 7-5. Casement effect of dimensions

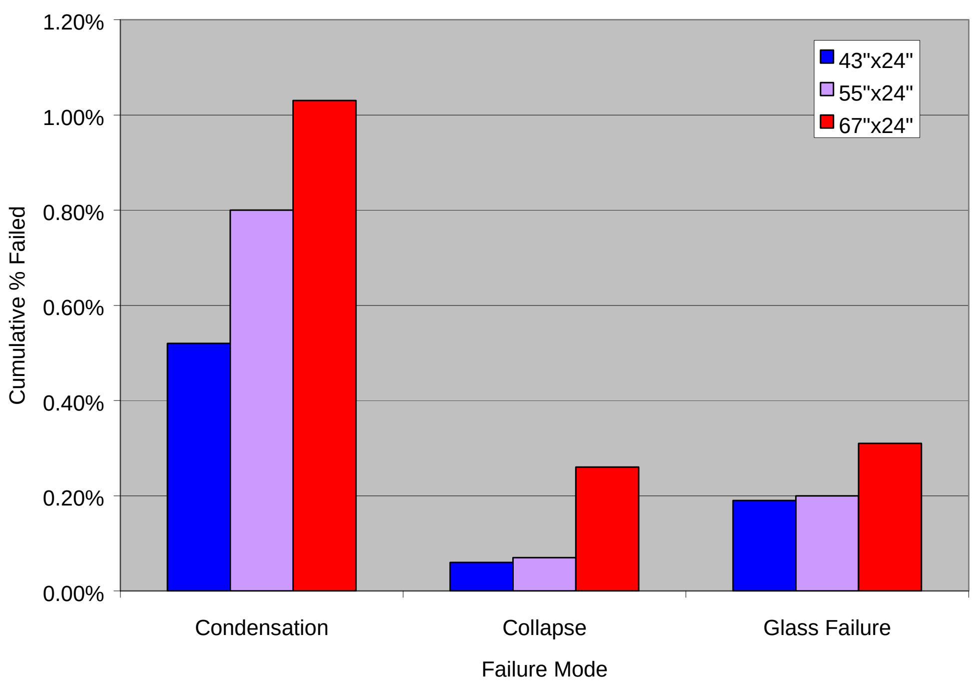

Figure 7-6. Casement failure mode effect of dimensions

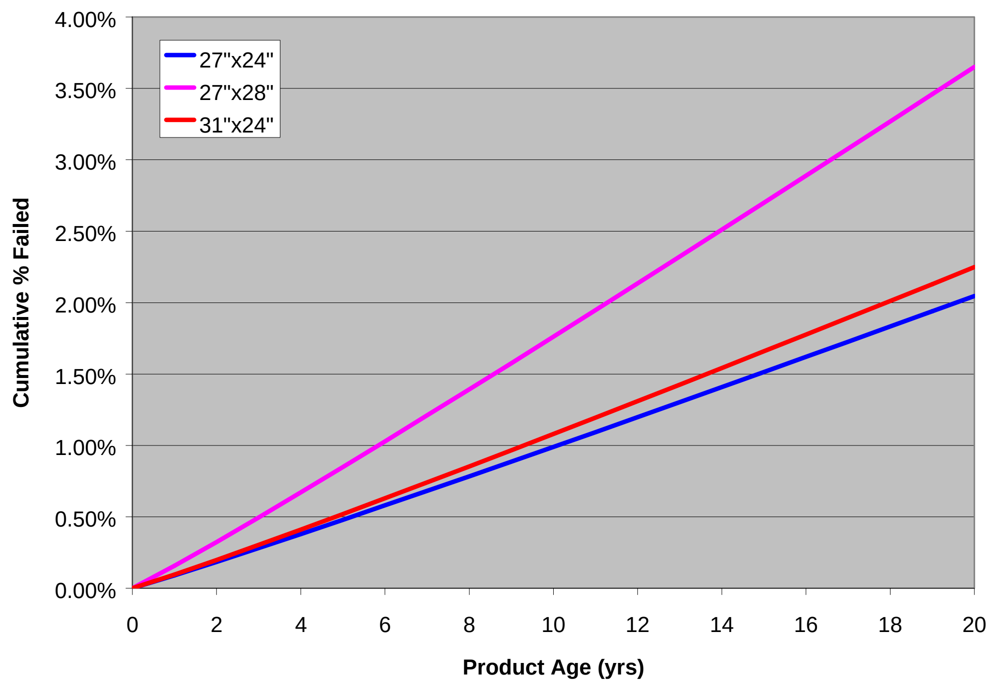

Figure 7-7. DH-2 effect of dimensions

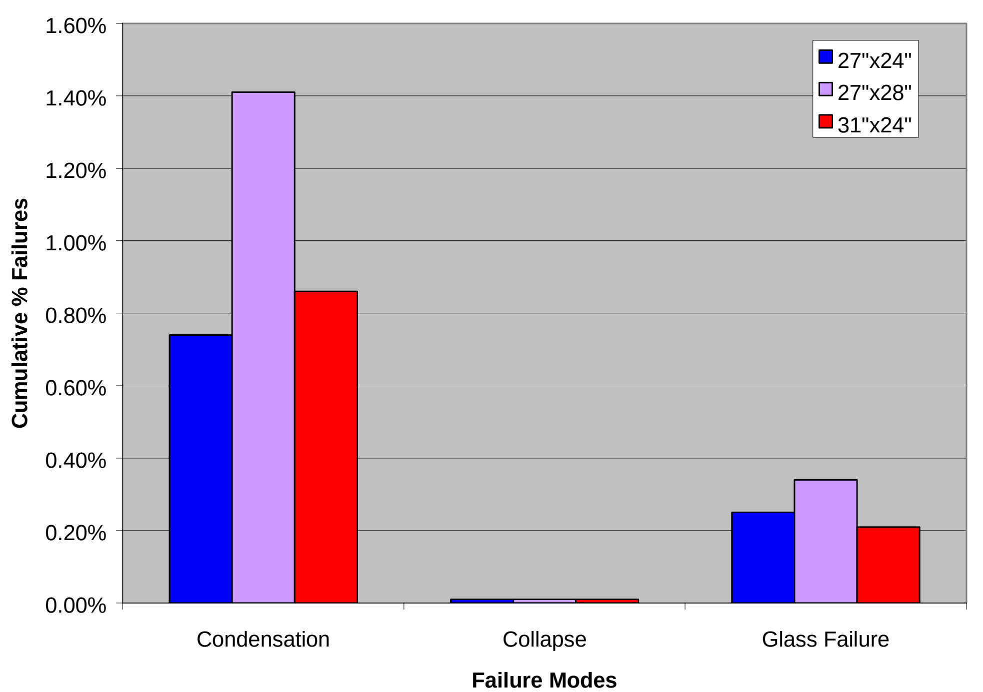

Figure 7-8. DH-2 failure mode effect of dimensions

Figures 7-9 and 7-10 show the dimension effect of the double hung product line, DH-1. The dimension effect of this product line shows a disparity with the area to projected failure hypothesis which was supported by the prior two product lines. In this case the product with smallest area exhibits the highest projected product failures. This trend is observed in both the condensation and glass failure projections. Collapse failures remain relatively constant across the products. Reported condensation failure increase 120% from the lowest reported frequency (for 32"x24") units to that of the smallest area (20"x28"). Reported glass failures increase 80% from the lowest reported frequency to that of the smallest area. There is insufficient information to derive a hypothesis for this seeming disparity with that of the previous product lines. The contrary trends seen with this product line may indicate that either undefined process variables are driving the trends, or that special cause variations in the data shift the trends in such a matter that generalizations can not be made regarding system reliability as a function of dimensions.

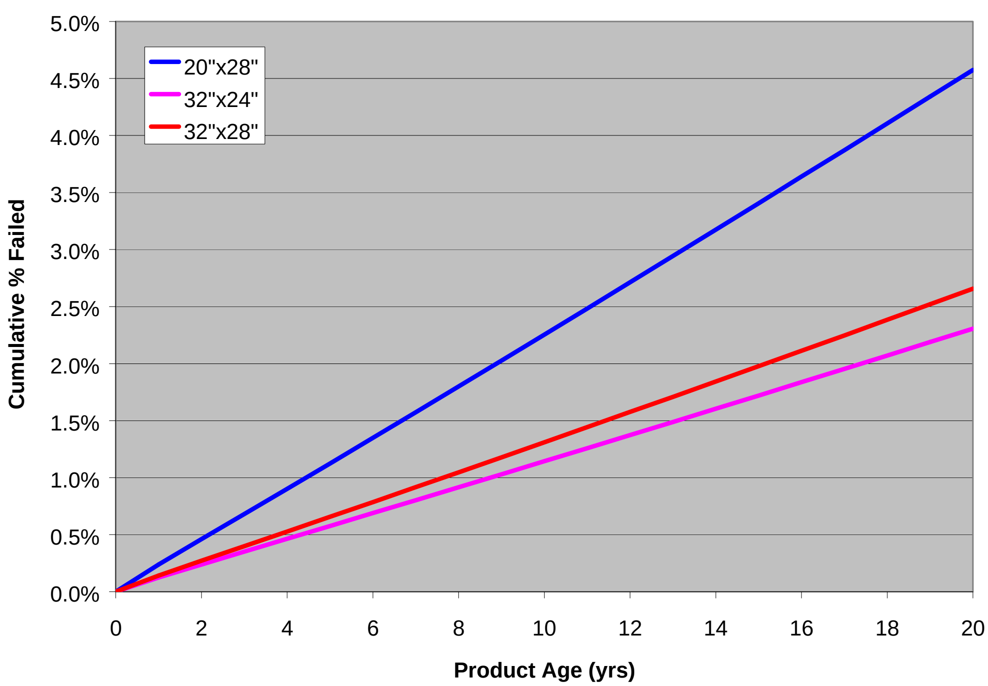

Figure 7-9. DH-1 effect of dimensions

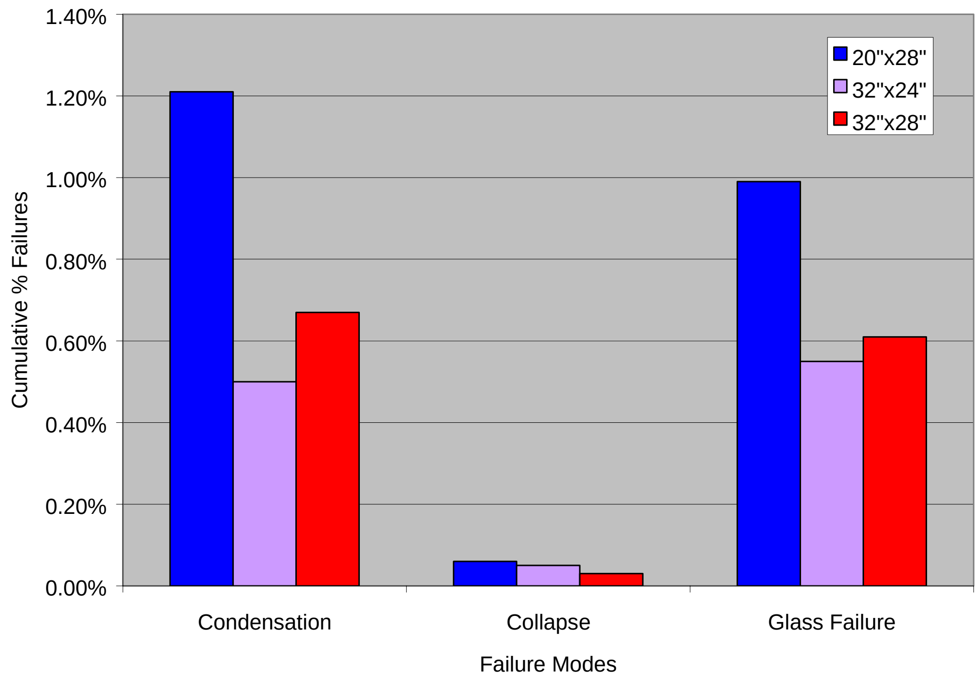

Figure 7-10. DH-1 failure mode effect of dimensions

An attempt is made, through the next series of charts, to determine the effect of environment on system reliability. Figures 7-11 and 7-12 demonstrate the projected system and failure mode effect of environment for the casement product. Figures 7-13 and 7-14 demonstrate the projected system and failure mode effect of environment for the DH-2 double hung product.

Sufficient sales volume and failure data were present in only two environmental regions for projections of casement product. The environmental regions are the low temperature, low precipitation area of the upper western non-coastal states, and the low temperature, high precipitation regions of the Midwest, great lakes and north eastern states. Sufficient data was only available for the 43"x24" dimension product in these regions. The projected product performance in Figure 7-11 shows that higher reported failure rates are expected in the low temperature, high precipitation regions, rather than the low temperature, low precipitation regions. It is seen from the failure mode projections that increased condensation failures drive this increase system failure rate.

A hypothesis which would explain the higher failure rate in more humid and damp climates is that since more moisture is in the environment, there is more available for condensation on the unit as the temperature drops below the dew point. Also the presence of more external moisture provides a greater forcing function for driving the moisture into the IG unit.

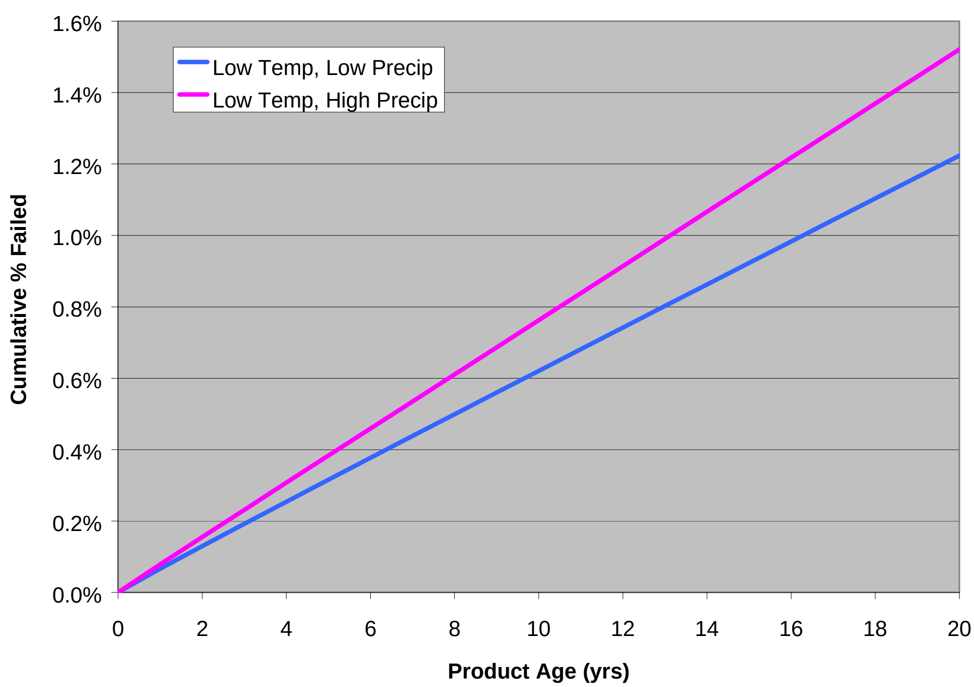

Figure 7-11. 43”x24” Casement effect of environment

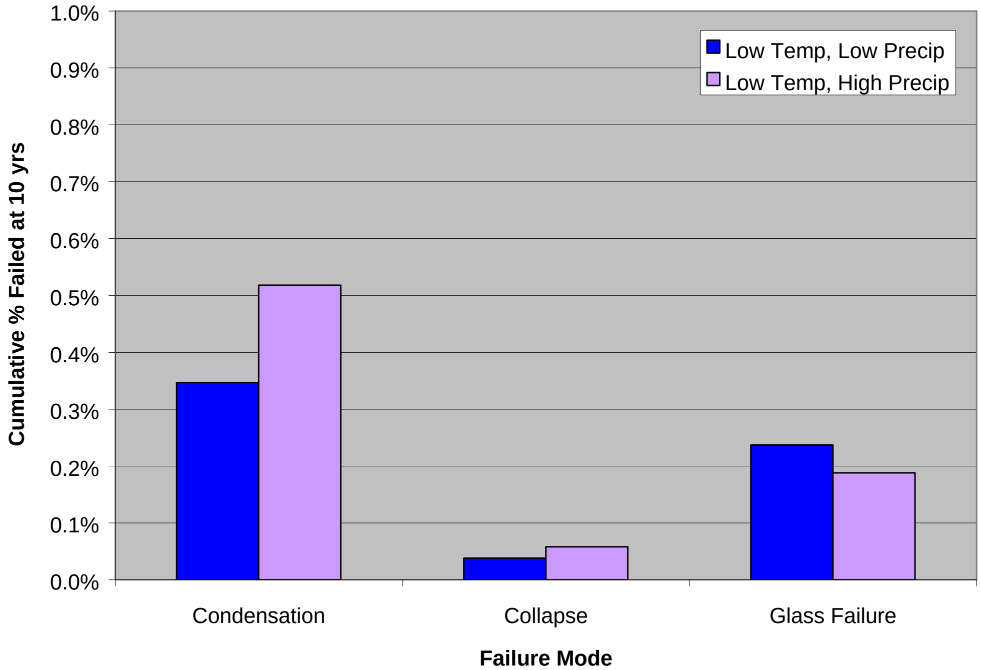

Figure 7-12. 43”x24” Casement failure mode effect of environment

Sufficient sales volume and failure data were present in only two environmental regions for projections of double hung product, DH-2. The projected system failure rates are shown in Figure 7-13. The failure mode contribution to the failure rates are shown in Figure 7-14. The environmental regions are the high temperature, high precipitation area of the southern coastal states, and the low temperature, high precipitation regions of the Midwest, great lakes and north eastern states. Sufficient data was only available for the 31”x24” dimension product in these regions.

The project product performance in Figure 7-13 shows that higher reported failure rates are expected in the low temperature, high precipitation regions, rather than the high temperature, high precipitation regions. It is again seen from the failure mode projections that increased condensation failures drive this increase system failure rate.

The hypothesis to explain this performance is straightforward. Both environments provide a substantial driving function to force moisture into the interior IG space. As moisture permeates the seals and saturates the desiccant, condensation will only be observed if the temperature drops below the dew point of the IG interior. The low temperature environment provides greater opportunity for this to happen. Thus there is a higher frequency of this occurrence in the Midwest and Northeast compared to the southern coastal regions.

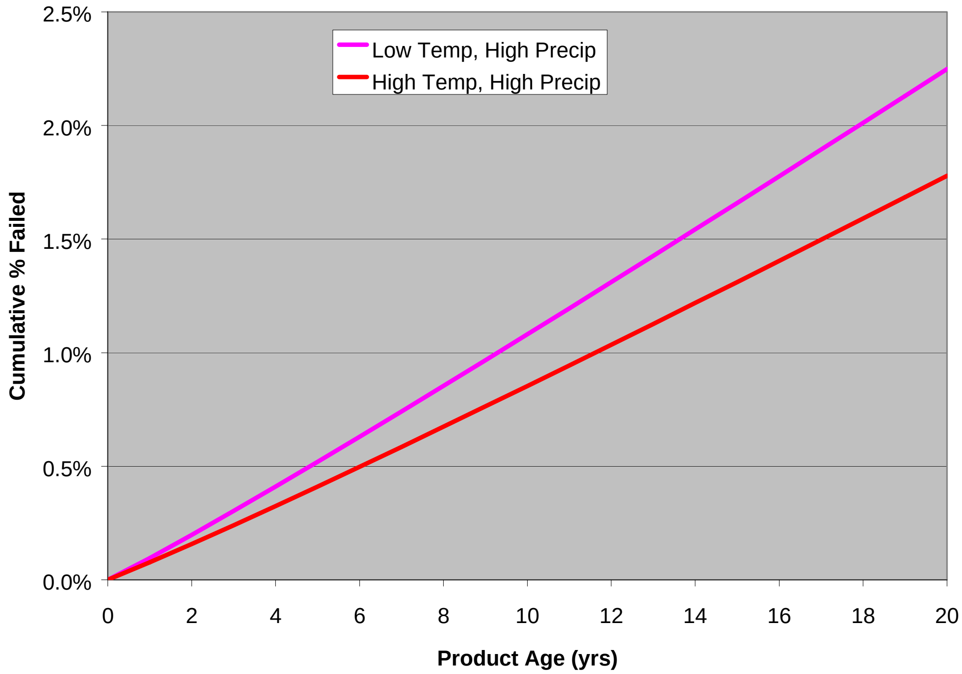

Figure 7-13. 31”x24” DH-2 effect of environment

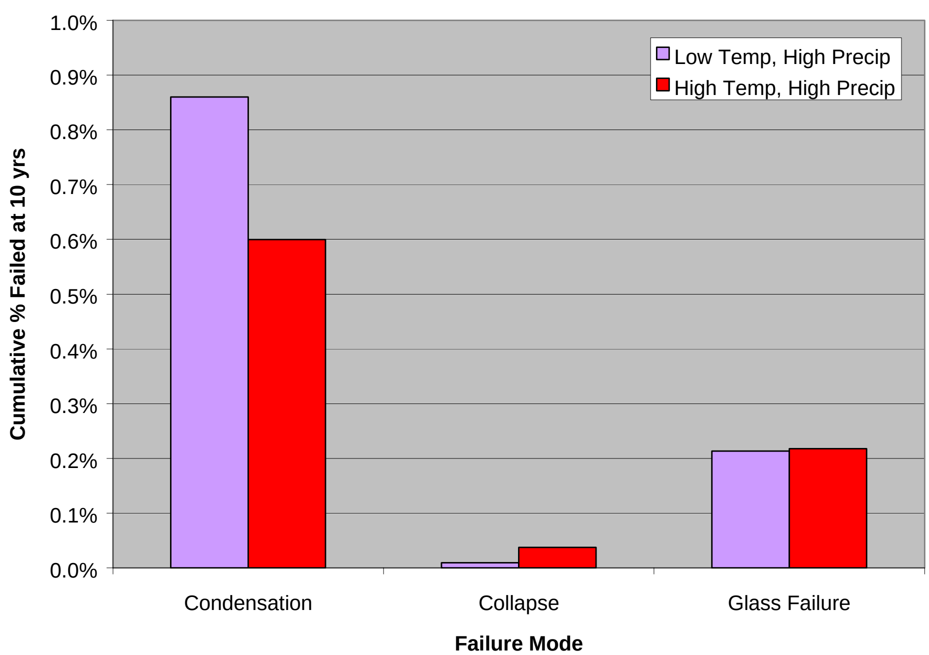

Figure 7-14. 31”x24” DH-2 failure mode effect of environment

A final comparison attempted regarded the effect of glass thickness on system reliability performance. This comparison is seen in Figure 7-15. Products within the casement line are compared which have 2 mm versus 3mm glass. Comparisons are made regarding the expected failures at 10 years of product in the Midwest and Northeast regions. Unfortunately, the product mix makes it impossible to compare the effects of glass thickness with all other variables held constant. Specifically, for the dimensions of the 2 mm product are 67”x24”; where the dimensions for the 3 mm product are 67”x32”. Also the distance between the glass panes is somewhat less for the 3 mm glass than for the 2 mm glass product. Nonetheless, keeping the limitations of the comparison in mind it was thought to be instructive to compare the two units.

From observing the chart, it is clear that the overall failure rates are expected to be reasonably similar. The reported condensation failures and the glass failures are also reasonably similar. A seemingly significant difference is seen in the amount of reported collapse of the two units, however. It appears that units with thinner glass tend to have higher rates of collapse than for thicker glass units. These results appear consistent with physics expectations, since it has been previously discussed that glass thickness is a driving factor in the flexural resistance of the glass to bending and collapse.

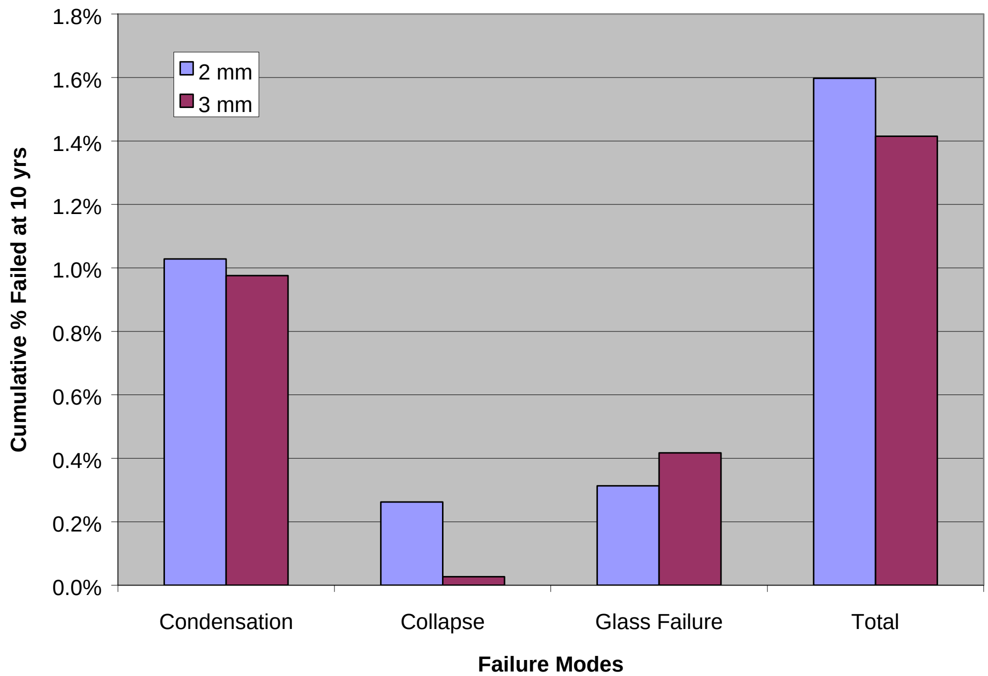

Figure 7-15. Casement Glass Thickness Effect

Summary

The methodology for extracting reliability estimates from field data, given product knowledge, has been developed. The feasibility of such projections as well as their benefits and limitations have been discussed. It is evident reliability approaches can be used to develop durability projections of IG project, given sufficient field data and product knowledge. The amount of information that can be gained from the projections is limited by quantity and resolution of both failure data and sales data.

The projections were made from the perspectives of the consumer's perceptions. Specifically, units are considered to fail if the consumer perceives a failure and then reports the failure.

The specific example demonstrated that with the quantity and quality of data, hypotheses could be developed regarding the durability of the box spacer product. The effect of environmental attributes and design attributes could be considered with respect to the various hypotheses of failure. Although the hypotheses could not be accepted or rejected with a degree of statistical confidence, the results do support the most likely estimate of the parameter's effects on durability.

In judging the precision and validity of the statements, two particular underlying assumptions should be considered. First, it was necessary to assume the reported failure codes accurately represent the failure mode of the failure unit. Although there is some underlying reporting error, there is also a specific potential for misrepresentative failure coding among the available codes. Specifically, it is quite plausible that collapsed failures are reported as condensation failures. Since an observed effect of collapse is condensation, it is quite possible this visual effect of the failure was reported, rather than the underlying failure mode.

A second underlying assumption which should be evaluated is the assumption that customer sensitivity to product failure is constant over time. It is possible, for instance, that the second owners of a home will have decreased performance expectations relative to the initial homeowners. If this is true, then customer sensitivity decreases over time. It was beyond the scope of this first phase effort to model this potential degradation in customer perception. Such changes in sensitivity can be considered in the subsequent phase II effort, however.

Appendix 2:

Relevant ASTM Standards

C 1036-01	Standard Specification for Flat Glass
C 1048-97b	Standard Specification for Heat-Treated Flat Glass-Kind HS, Kind FT Coated and Uncoated Glass
C 1164	Practice for Evaluation of Limestone or Lime Uniformity from a Single Source
C 1172-96e1	Standard Specification for Laminated Architectural Flat Glass
C 1203	Specification for Flat Glass
C 1265-94 (1999)	Standard Test Method for Determining the Tensile Properties of an Insulating Glass Edge Seal for Structural Glazing Applications
C 1279-00e1	Standard Test Method for Non-Destructive Photoelastic Measurement of Edge and Surface Stresses in Annealed, Heat-Strengthened, and Fully Tempered Flat Glass
C 1294-01	Standard Test Method for Compatibility of Insulating Glass Edge Sealants with Liquid-Applied
C 1376-97	Standard Specification for Pyrolytic and Vacuum Deposition Coatings on Glass
C 1422-99	Standard Specification for Chemically Strengthened Flat Glass
C 148	Test Methods for Polariscope Examination of Glass Containers
C 158-95 (2000)	Standard Test Methods for Strength of Flexure (Determination of Modulus of Rupture)
C 162	Terminology of Glass and Glass Products
C 162-99	Standard Terminology of Glass and Glass Products
C 336	Test Method for Annealing Point and Strain Point of Glass by Fiber Elongation
C 338	Test Method for Softening Point of Glass
C 346	Test Method for 45-deg Specular Gloss of Ceramic Materials
C 598-93 (1998)	Standard Test Method for Annealing Point and Strain Point of Glass by Beam Bending
C 717	Terminology of Building Seals and Sealants
C 724	Test Methods for Acid Resistance of Ceramic Decorations on Archetural-Type Glass
C 770-98	Standard Test Method for Measurement of Glass Stress - Optical Coefficient
C 813-90 (1999)	Standard Test Method for Hydrophobic Contamination on Glass by Contact Angle Measurement, Referenced: D1193
C 978-87 (1996)	Standard Test Method for Photoelastic Determination of Residual Stress in a Transparent Glass
C1036-01	Standard Specification for Flat Glass
C1045-01	Standard Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions
C1199-00	Standard Test Method for Measuring the Steady-State Thermal Transmittance of Fenestration Systems Using Hot Box Methods
C1249-93	Standard Guide for Secondary Seal for Sealed Insulating Glass Units for Structural Sealant Glazing
C1265-94	Standard Test Method for Determining the Tensile Properties of an Insulating Glass Edge Seal for Structural Glazing Applications
C1294-01	Standard Test Method for Compatibility of Insulating Glass Edge Sealants with Liquid-Applied
C1363-97	Standard Test Method for the Thermal Performance of Building Assemblies by Means of a Hot Box
C1369-97	Standard Specification for Secondary Edge Sealants for Structurally Glazed Insulating Glass Units
C1392-00	Standard Guide for Evaluating Failure of Structural Sealant Glazing
C1401-98	Standard Guide for Structural Sealant Glazing
D 1193	Specification for Reagent Water
D 2244	Test Method for Calculation of Color Differences from Instrumentally Measured Color Coordinates
D 2563-94	Standard Practice for Classifying Visual Defects in Glass-Reinforced Plastic Laminate Parts
E 1233	Test Method for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Cyclic Static Air Pressure Differential
E 1585-93	Standard Test Method for Measuring and Calculating Emittance for Architectural Flat Glass Products Using Spectrometric Measurements
E 179	Guide for Selection of Geometric Conditions for Measurement of Reflection and Transmission Properties of Materials
E 1887	Test Method for Fog Determination
E 284	Terminology of Appearance
E 308	Practice for Computing the Colors of Objects by Using the CIE System
E 330-97e1	Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference
E 331-00	Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference
E 380	Practice for Use of the International System of Units
E 4	Practices for Load Verification of Testing Machines
E 41	Definitions of Terms Relating to Conditioning
E 546-88 (1999) e1	Standard Test Method for Frost Point of Sealed Insulating Glass Units

E 547-00	Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference
E 576-88 (1999) e1	Standard Test Method for Dew/Frost Point of Sealed Insulating Glass Units in Vertical Position
E 631	Terminology of Building Constructions
E 77	Test Method for Inspection and Verification of Thermometers
E 773-01	Standard Test Method for Accelerated Weathering of Sealed Insulating Glass Units
E 774-97	Standard Specification for the Classification of Durability of Sealed Insulating Glass Units
E 903	Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating
E 932	Practice for Describing and Measuring Performance of Dispersive Infrared Spectrophotometers
E 997-01	Standard Test Method for Structural Performance of Glass, in Exterior Windows, Curtain Walls, and Doors Under the Influence of Uniform Static Loads by Destructive Methods
E 998-84 (1999)	Standard Test Method for Structural Performance of Glass in Windows, Curtain Walls, and Doors Under the Influence of Uniform Static Loads by Nondestructive Method
E1017-88	Standard Specification for Generic Performance Requirements for Exterior Residential Window
E1105-00	Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Cyclic Static Air Pressure Difference
E1175-87	Standard Test Method for Determining Solar or Photopic Reflectance, Transmittance, and Absorptance of Materials Using a Large Diameter Integrating Sphere
E1233-00	Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Cyclic Static Air Pressure Differential
E1300-00	Standard Practice for Determining Load Resistance of Glass in Buildings
E1332-90	Standard Classification for Determination of Outdoor-Indoor Transmission Class
E1376-90	Standard Test Method for Measuring the Interzone Attenuation of Sound Reflected by Wall Finishes and Furniture Panels
E1423-99	Standard Practice for Determining the Steady State Thermal Transmittance of Fenestration Systems
E1424-91	Standard Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure and Temperature Differences Across the Specimen
E1425-91	Standard Practice for Determining the Acoustical Performance of Exterior Windows and Doors
E1748-95	Standard Test Method for Evaluating the Engagement Between Windows and Insect Screens as an Integral System
E1886-97	Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors, and Storm Shutters Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials
E1887-97	Standard Test Method for Fog Determination
E1996-01	Standard Specification for Performance of Exterior Windows, Curtain Walls, Doors and Storm Shutters Impacted by Windborne Debris in Hurricanes
E2010-01	Standard Test Method for Positive Pressure Fire Tests of Window Assemblies
E2025-99	Standard Test Method for Evaluating Fenestration Components and Assemblies for Resistance to Impact Energies
E2068-00	Standard Test Method for Determination of Operating Force of Sliding Windows and Doors
E2141-01	Standard Test Methods for Assessing the Durability of Absorptive Electrochromic Coatings on Sealed Insulating Glass Units
E2188-02	Standard Test Method for Insulating Glass Unit Performance
E2189-02	Standard Test Method for Testing Resistance to Fogging in Insulating Glass Units
E2189-02	Standard Test Method for Testing Resistance to Fogging in Insulating Glass Units
E2190-02	Standard Specification for Insulating Glass Unit Performance and Evaluation
E283-91	Standard Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen
E330-97	Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference
E331-00	Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference
E405-89	Standard Test Methods for Wear Testing Rotary Operators for Windows
E546-88	Standard Test Method for Frost Point of Sealed Insulating Glass Units
E547-00	Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference
E576-88	Standard Test Method for Frost Point of Sealed Insulating Glass Units in the Vertical Position
E-6 P1	Proposed Recommended Practices for Testing Seal Longevity of Sealed Insulating Glass Units
E-6 P2	Proposed Recommended Practices for Testing Seal Durability of Sealed Insulating Glass Units
E-6 P3	Proposed Specification for Sealed Insulated Glass Units

Appendix 3

SealSim 1.1 User Manual

SealSim 1.1 User Manual

A PC program for the determination of the Durability of Insulating Glass Units

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Contents

1 SealSim 1.1, an introduction

1.1 What is SealSim 1.1?

SealSim 1.1 is a state-of-the-art, Microsoft Windows™-based computer program developed for the US Department of Energy by TNO TPD and Aspen Research Corporation, for use by manufacturers, engineers, educators, students, architects, and others to determine the durability of Insulating Glass Units (IGU). As a function of time, SealSim 1.1 simulates the behaviour of an Insulating Glass Unit, exposed to realistic or user-defined weather climates. Stresses and strains in the IGU are calculated as a function of time, together with temperature distributions, gas permeation effects (gas loss, desiccant loading), dew point temperature, U-factor as function of time, etc.

The current version of SealSim 1.1 supports double-glazing Units, where the spacer system is either a Thermo Plastic Spacer (TPS) or Box type spacer. An Impression of the representation of an IGU w/Box Spacer in SealSim 1.1 and indication of physical effects modelled is given below. For the determination of solar properties of glazing systems, SealSim 1.1 uses the International Glazing Database of LBNL, which is also used by OPTICS and WINDOW.

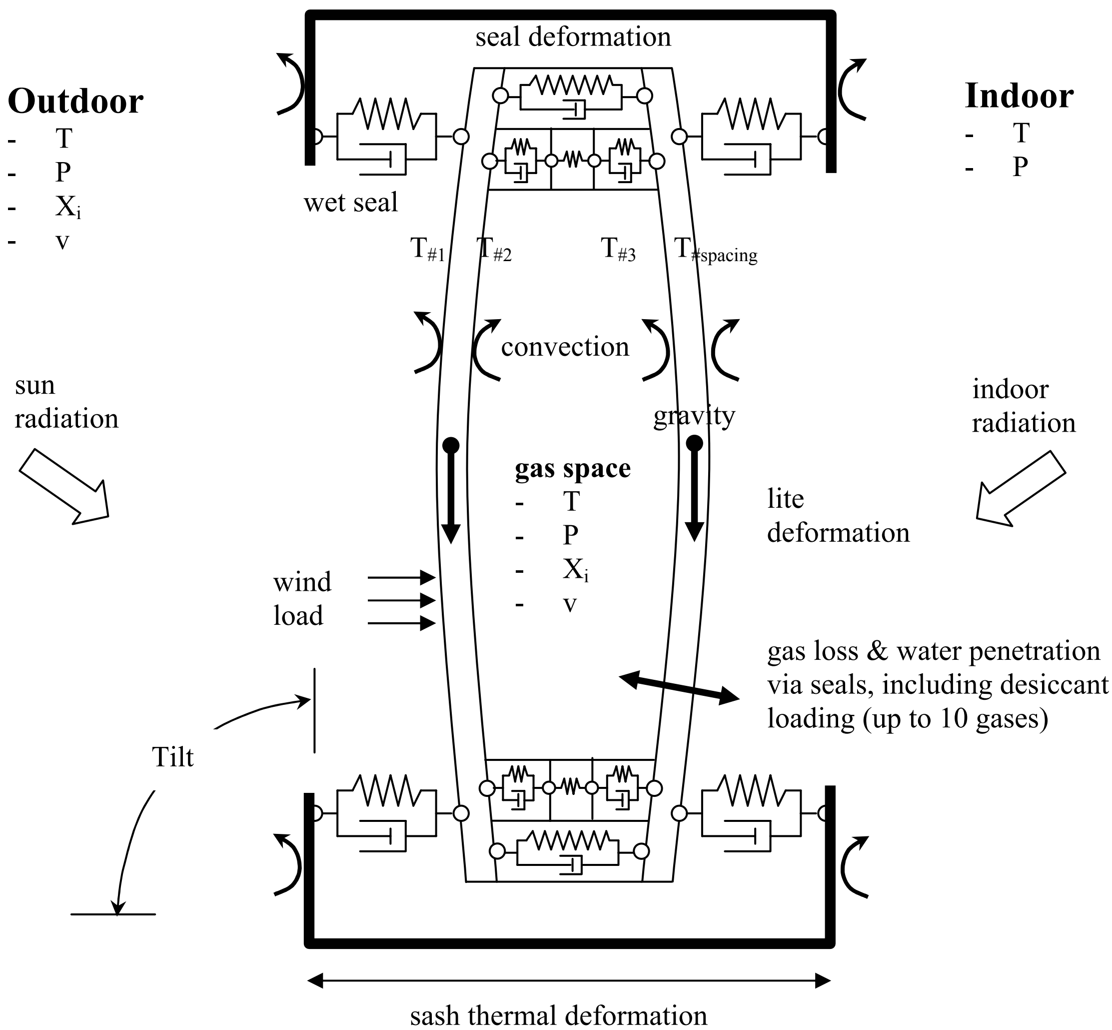

Figure 1, Impression of the representation in SealSim 1.1 of an IGU (Box Spacer) and indication of physical effects modelled (T=temperature, P=pressure, X_i=composition, v=velocity)

a b

Figure 2 SealSim 1.1 currently supports the following spacer systems (a) Thermo Plastic Spacer (b) Box type spacer.

1.2 Goal of the SealSim 1.1 simulations

The goal of the SealSim 1.1 simulations is to predict the IGU's average lifetime, expressed in terms of the "Durability Index", together with the associated failure mechanisms. Knowing the Durability Index of a particular IGU and its most probable failure mechanism, this can be compared with other IGU's. Thus a quantified measure is available to decide which IGU is more durable and why (taking into account the limitations of the physical models). This information can be used for example to select a specific IGU design to fit a certain application according to needs, or, for example, to improve the design of an IGU. How the predicted Durability Index relates to the actual durability of an IGU is not known, simply because sufficient experimental data is lacking for describing the behaviour of IG Units over extended periods of time together with a lack of knowledge of the conditions it is subjected to and initial state of the IGU at the time of manufacturing.

1.3 How does SealSim 1.1 simulate the response of an IGU in time?

In order to simulate the IGU behaviour in time, the conditions of the IGU must be defined; together with the weather and or climate that the IGU is subjected to. Part of the system description consists of, in part, the specification of the IGU dimensions, its position and orientation on earth, type of spacer system, gas fill composition, glass lite properties, solar (infrared) properties, initial conditions, material properties, etc. Using physical models of the IGU, SealSim 1.1 calculates the response of the IGU in time. These physical models are described in more detail in separate documents provided with the SealSim 1.1 program.

1.4 How does SealSim 1.1 deal with properties that show variation?

Most often variables that define an IGU are only known by approximation, or are known to vary between certain bounds, for example as a result of manufacturing practises. To deal with these kinds of variations, SealSim 1.1 follows a statistical approach, in which rather than specifying definite values for variables, probability distributions are entered. In this way for example, variation of the interface strength of the inner seal polymer with glass can be accounted for. One such a probability distribution for example is a normal distribution, which is uniquely defined by a mean value and a standard deviation. Prior to a simulation run, SealSim 1.1 determines with the help of a built in random generator, a set of definite values for the group of properties that have been attributed a probability distribution. This is done in such way, that if this procedure were repeated over an over, and all the definite variable values collected, they would show the probability distribution which was assigned. With this group of definite variable values, the behaviour of the IGU is simulated in time, resulting in a prediction for its lifetime and failure mechanism. Such a simulation sequence, "determining a group of definite values with a random generator" and the subsequent by running a transient simulation, is called a "Monte Carlo Simulation Run". So a complete "SealSim 1.1 Simulation Run", consists of one or more "Monte Carlo Simulation Runs" (up to a user specified number). The results of all these Monte Carlo Simulation Runs are statistically evaluated by SealSim 1.1, resulting in a prediction of the average lifetime of the IGU, standard deviation in lifetime, fraction of runs that resulted in a particular failure, the Durability Index, etc.

1.5 To which SealSim 1.1 input data probability distributions can be attributed?

Via the SealSim 1.1 Graphical User Interface (GUI), probability distributions can be set only for material properties in this version of SealSim 1.1, and not for climate data, dimensions, etc. The latter data needs to be varied outside SealSim 1.1. However the SealSim 1.1 problem definition file, that contains values of all variables that define the IGU (including material properties), can be manually edited, giving the possibility to attribute distributions to almost every variable imaginable. This option has not been tested thoroughly in SealSim 1.1.

1.6 What is the actual definition of the "Durability Index"?

The Durability Index as calculated by SealSim 1.1 is derived from the average lifetime of an IGU, which is obtained from running a large number of Monte Carlo Simulation Runs. Actually the Durability Index is set equal to the calculated average lifetime of the IGU.

So why do we introduce the term "Durability Index" and why do we not just use the "average lifetime" instead? To answer this question, we first have to define what is the average lifetime? The lifetime of an IGU is defined as that instant in time, calculated from simulation start, at which a user set limit for durability is exceeded. When this happens the IGU is considered to have failed. Note that it is up to the user to define if simulation should begin with the time of manufacturing of the IGU, or time of installation of the IGU, or some other time. An example of such a failure limit is the dew point temperature of the IGU. If the temperature of the IGU drops below the dew point temperature, condensation will occur on the glass lites, which is unacceptable from the viewpoint of vision. What kind of durability failures are acceptable or not, and what failure limits should be employed, is a matter of taste or individual judgement, and the perception largely varies between users. Up till now there is no unique and fully accepted definition of durability. Therefore SealSim 1.1 offers the user the ability to select his/her own durability criteria and limiting values, giving full control over the users perception.

The actual simulation time period used, to follow the behaviour of the IGU in time, will have an affect on the predicted value for the average lifetime. This will be explained below. SealSim 1.1 simulates the behaviour of the IGU over a limited period in time. If the IGU does not fail, its theoretical lifetime will be equal to the simulation time period, or much more likely, even longer. SealSim 1.1 will take the specified simulation time period as a lower bound for its lifetime, as this is the best information available. Unless the simulation time period is extended and the IGU fails in all Monte Carlo Simulation Runs, the theoretical lifetime is known. In the other case the predicted average lifetime is a lower bound for the actual lifetime.

Back to our question, why not use the term average lifetime only, instead of Durability Index? Using the term average lifetime to compare IGU's is very dangerous, as the comparison is only fair when the same failure criteria and limits are used, and also the IGU's are observed or tracked over at least the same extent of time, and are subjected to identical conditions with respect to climate, etc. So when mentioning the lifetime of a unit, it is only fair, if also at the same time the failure criteria and limits are mentioned, and other important conditions such as weather or climate, the time period the IGU is tracked or observed, and if it concerns a predicted or measured value. Concerned that, in this practice, these kinds of subtleties in information might get lost; we prefer the more neutral term Durability Index.

1.7 How to use the Durability Indexes to compare different IGU's?

In the previous paragraph we argued that a comparison of IGU's based on their respective Durability Indexes, is only fair and objective, if identical failure criteria and limits are used, together with identical other conditions such as weather or climate and time periods throughout the IGU's are observed or tracked. Only when these conditions are met, can we say, for example, that "IGU number one is likely to be better than IGU number 2 with respect to durability". Of course, when saying this, the limitations of the physical models in SealSim 1.1 should always be taken into account.

IMPORTANT NOTICE

The Durability Index is based on simulation of IGU behaviour over the user defined simulation time period. An IGU with a higher Durability Index is considered to have a longer lifetime than a unit with a lower Durability Index. As generally not all units will fail within the simulated timeframe, the Durability Index is a conservative estimate. This value can be improved by running the simulation over a longer time period (up to the user). The Durability Index is based on simulations and is not validated against real life data. At the best it therefore can be used to compare different IGU designs, taking into account the limitations of the physical model, though no guarantee can be given that this is correct. When comparing IGU designs based on the Durability Index, the comparison is only fair if the simulation time period and all conditions applied are the same for all designs.

1.8 Number of Monte Carlo Runs required to obtain statistical relevant output

When a SealSim 1.1 Simulation is performed, using probability distributions for material properties, the results, e.g. occurrence of failures, are evaluated in a statistical manner. The results are only meaningful when enough statistical information is collected, that is when a sufficient number of Monte Carlo Runs are performed. The user therefore is advised to perform enough additional Monte Carlo runs until the results do not change significantly anymore. But what is significant?

This leads us to the question if one can say, a priori, before actually running a SealSim 1.1 Simulation, how many Monte Carlo Simulation Runs are required, in order to obtain statistically relevant output? Can one also say in which way the number of runs is related to the number of variables that are attributed a probability distribution? Say we assume a Normal distribution. In practice the answer is: No. Only if SealSim 1.1 were a linear model (that is, if the output were a linear function of the input variables), and the variables would be mutually independent, can the number of runs be determined a priori. This is further explained in one of the next chapters. The physical models present in SealSim 1.1 however are nonlinear. So, the answer is No. But if the answer is No, how does one then determine if the output is statistical relevant? In that case, the simplest thing to do is to run a couple of simulations, analyze the results, and assuming that the outcome is Normally distributed, determine how many additional simulation runs have to be performed, to obtain the accuracy you desire. If necessary, this procedure must be repeated. Tools to help you with the statistical analysis are planned for a future version of SealSim 1.1.

1.9 This version of SealSim 1.1

Though much care was taken to test the correct implementation of physical sub models in SealSim 1.1, make the graphical user interface intuitive, making it robust, and to check all options that are available in SealSim 1.1, it will certainly suffer from the deficiencies of a first release. We are very interested in hearing your comments so we can constantly improve SealSim 1.1 and make it more valuable to you. The development of Physical Models, forming the basis of SealSim 1.1, is an ever-continuing task, and in the next versions of SealSim 1.1 we would very much like to add more details and realistic effects.

1.10 Acknowledgement

TNO TPD, for Aspen Research Corporation, developed SealSim 1.1 in the framework of the project "An Insulating Glass Knowledge Base", as sponsored by the U.S. Department of Energy, DE-FC26-

01NT41258. We thank Aspen Research Corporation and the U.S. Department of Energy for providing the opportunity to develop SealSim 1.1.

The Lawrence Berkeley National Laboratory, Windows & Daylighting Group, in particular Robin Mitchell, Christian Kohler and Dariush Arasteh, are kindly thanked for making the International Glazing Database available for SealSim 1.1, and Richard Versluis of TNO Buildings & Construction for intermediating. Database information can be found on http://windows.lbl.gov/materials/IGDB.

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Please address comments, questions and suggestion to:

Aspen Research Corporation
1700 Buerkle Road
St Paul, Minnesota 55110

2 Installation

2.1 System Requirements

SealSim 1.1 requires the following minimum computer requirements:

- Pentium class or better.
- For optimal operation, 64 MB or more of RAM is preferable.
- Preferred operating system: Microsoft Window XP.
- Hard disk drive with at least 40 MB of available disk space

2.2 Before Installing SealSim 1.1

Close all programs before installing SealSim 1.1 and uninstall any previous versions of the SealSim 1.1 program before starting the installation of this version.

2.3 Installing SealSim 1.1

Before installation you are asked to read and sign the End Users License Agreement. Put SealSim 1.1 installation CD in the appropriate drive. The installation program should automatically start when the CD is inserted, but if not, browse to the CD with MS Windows™ Explorer and double click on "Setup.exe". An Install shield Wizard window will appear saying that the installation program is preparing the installation. The installation will be self-explaining. You are asked to read and agree to the End Users License Agreement. If you do not have the ".NET" framework installed, you are asked to do so. Installation is required for running the SealSim 1.1 Graphical User Interface (GUI). You will be automatically directed to the web site where you can download ".NET". The default destination folder for the SealSim 1.1 program is C:\Program Files\TNO TPD\SealSim 1.1. It is advised not to change this default target directory, nor the SealSim 1.1 directory structure (see next figure), in order to guarantee proper functioning of SealSim 1.1. Note that SealSim 1.1 cannot run over the network, and should be installed on a local drive.

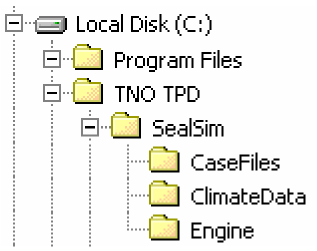

Figure 3 Default SealSim 1.1 program structure

Before starting SealSim 1.1, you may want to check if all files are present in the appropriate directories, as indicated below.

C:\Program Files\TNO TPD\SealSim
- IGUxmlDataTree.xml
- SealSim.exe
- sealsim.mdb
- TreeImagelistStrip.bmp
- GlazingTPD.mdb
- App.ico
- SealSimDataBaseDoc.xls
- SealSimReference.pdf
- Engine
- CaseFiles
- ClimateData

Figure 4 Contents SealSim directories

C:\Program Files\TNO TPD\SealSim\CaseFiles
- example.inp
- example.log
- example.out
- example.out2
- example.p1
- example.p2

C:\Program Files\TNO TPD\SealSim\ClimateData
- 94728.tm2
- indoor.ind
- trhseal.csl
- tseal.tsl

C:\Program Files\TNO TPD\SealSim\Engine
- Engine.exe
- w5cog.dll
- gasses.dll
- temperature.dll

*Figure 5 Contents SealSim 1.1 subdirectories (Note: of the example files only the input file *.inp may be included in the set up)*

It may be the case that, for example, the glazing database is not included in the set up, but supplied separately, as it is a rather large. You can always manually copy the missing files to their correct location. If a new version of the manual becomes available, you can overwrite the old one. When the installation is complete, SealSim 1.1 can be started from the Start button, Programs, SealSim.

2.4 End User License Agreement

SealSim 1.1 License

THIS SOFTWARE IS PROVIDED BY THE COPYRIGHT HOLDERS AND CONTRIBUTORS “AS IS" AND ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE ARE DISCLAIMED. IN NO EVENT SHALL THE AUTHORS OR CONTRIBUTORS BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.

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2.5 Installation Problems

2.5.1 *Not enough disk space*

If the installation program detects that there is not enough disk space, a screen showing how much is needed will appear.

2.5.2 *Previous Version Detected*

The installation will detect if SealSim 1.1 has been previously installed and will require that it be uninstalled before the new installation can proceed (see next Section "Uninstalling SealSim 1.1").

2.5.3 *Uninstalling SealSim 1.1*

To uninstall SealSim 1.1, open the Microsoft Windows™ Control Panel. Click on the Add/Remove Programs icon in the Microsoft Windows™. Control Panel and remove SealSim 1.1.

3 SealSim 1.1 Overview

3.1 Introduction

The following chapters are dedicated to the various input windows (nodes in the data trees) of SealSim 1.1.

3.2 Organisation of input and output

The following figures give an overview of the SealSim 1.1 Graphical User Interface (GUI) window.

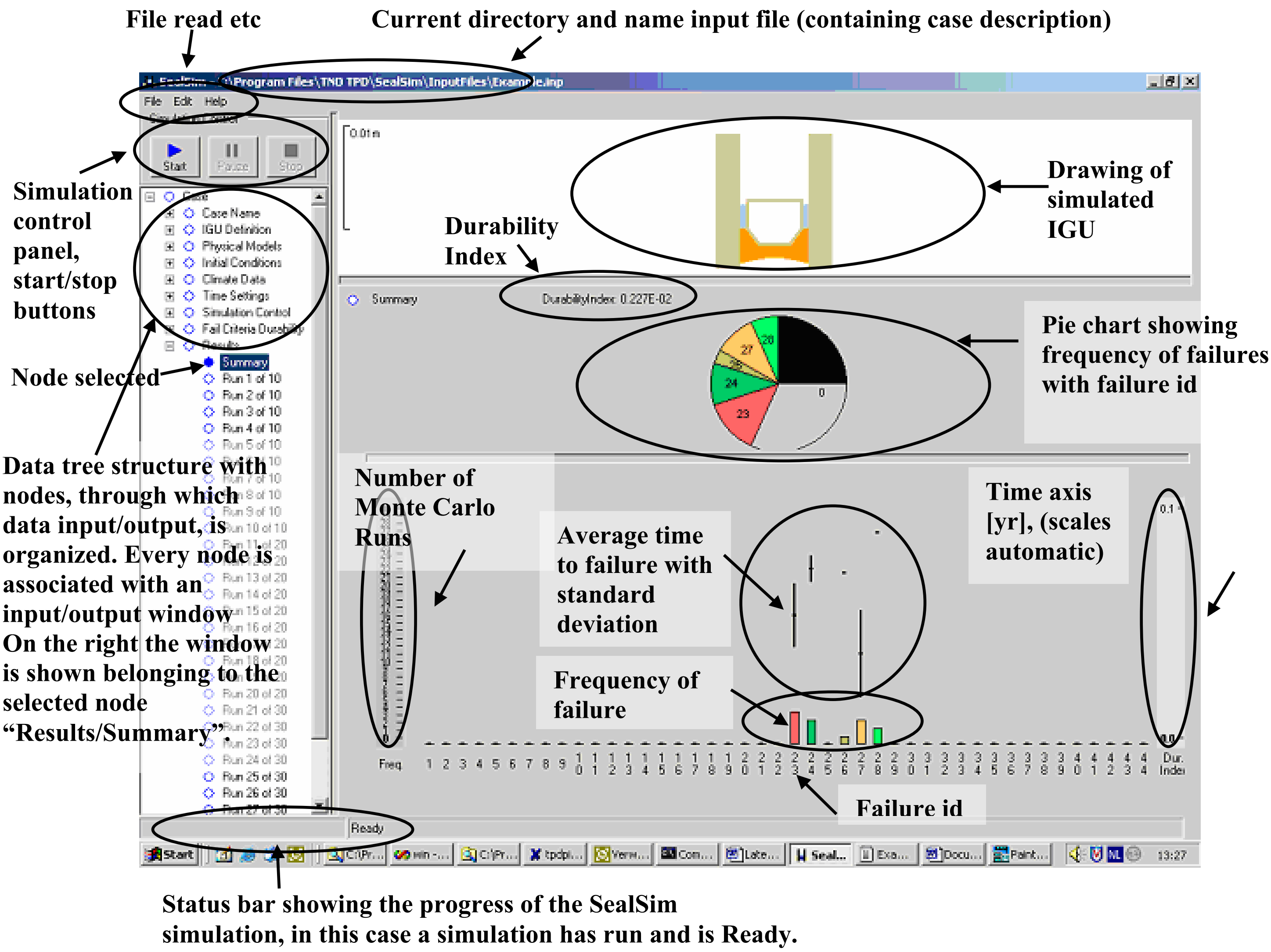


Figure 6- Overview SealSim 1.1 Graphical User Interface (GUI) window. The specific window shown belongs to node "Results/Summary".

Essentially, SealSim 1.1 input is organised in a data tree structure (shown on the left), under which nodes, sub nodes, etc are nested. Every node is associated with an input/output window (shown on the right) through which data can be entered defining the IGU and the conditions it is subjected to. This data is stored in a "Case Description File", also called "Input file". This input file is used by the SealSim 1.1 Engine, which performs the actual calculations. The GUI visually presents the output results of the SealSim 1.1 Engine. Both input files and output files can be saved to disk. The specific window shown above belongs to the node "Results/Summary". It contains a visualisation of output results of a complete SealSim 1.1 Simulation Run. As explained before, a complete "SealSim 1.1 Simulation Run" consists of one or more "Monte Carlo Simulation Runs".

3.3 *Data input and help with invalid data*

When SealSim 1.1 is started, all SealSim 1.1 nodes are the color “red”; all entry boxes defining a SealSim 1.1 case are blank. The user can start defining a case by filling in the empty entry boxes, or the user has the option to read in a pre-existing case (via Menu File, Submenu, and Open) and modify data. In this way the user also has the possibility to create his or her default case, from which to start.

The main nodes of the SealSim 1.1 data tree are repeated below. By clicking on the symbol ⊞ a node can be opened to reach the sub nodes below, and by clicking on ⊟ the node can be closed again:

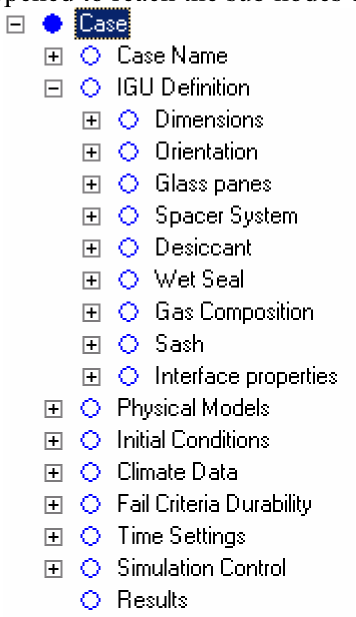


Figure 7-SealSim 1.1 input and output is organised in a nested data tree containing nodes

The following figure gives the input window belonging to the data tree node “IGU Definition/Dimensions”. On the right, two “data entry boxes” are present, through which the width and the height of the glass lites can be entered, with unit’s meters.

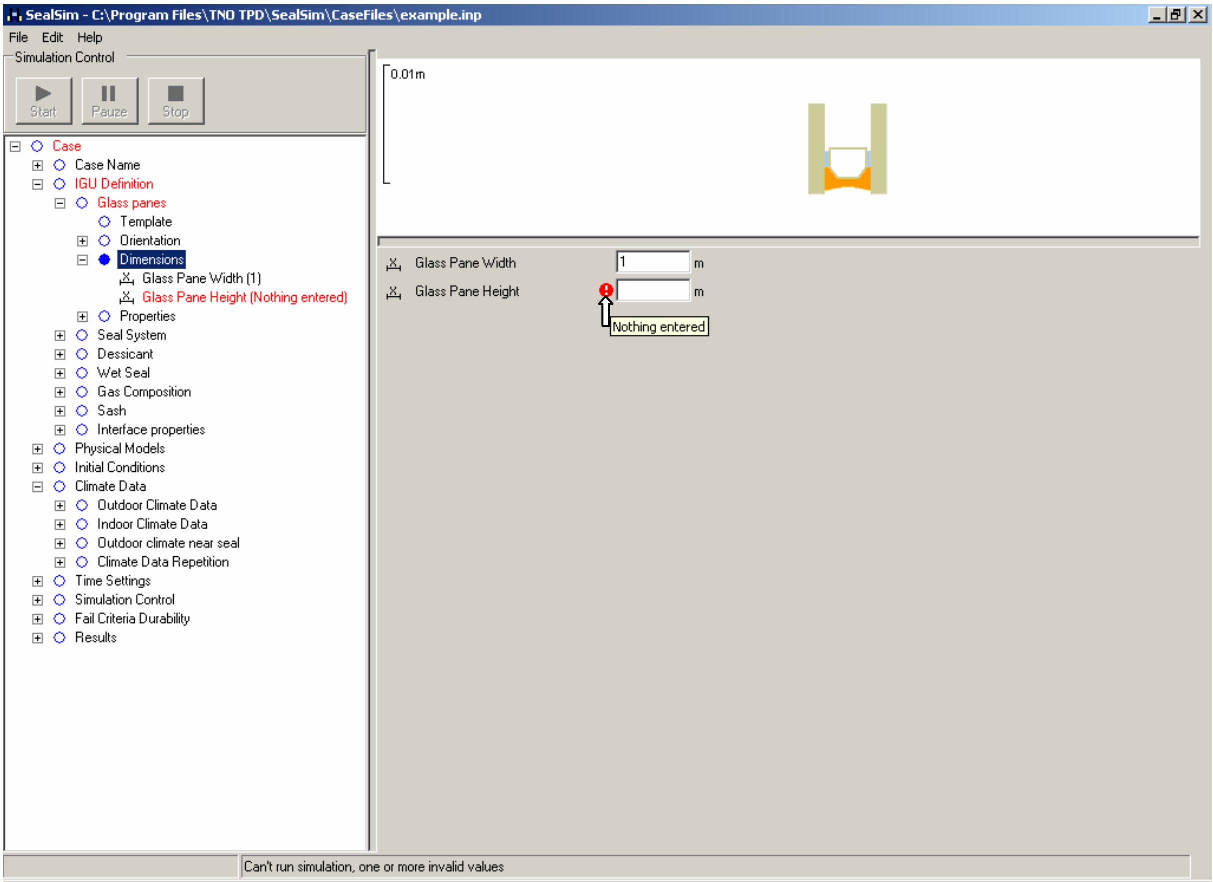


Figure 8, Sample input window belonging to sub node "Dimensions"

In this especially prepared case, of the whole case description, only the two entry **(*)** boxes shown were left blank, all the other entry boxes belonging to other nodes where filled with valid values. The first entry box has the value 1 entered. The GUI visually indicates invalid or missing data, and shows this in two ways:

(1) By showing an exclamation mark  to the left of the entry box. If the mouse pointer is moved over the exclamation mark, it will show a message, explaining what is wrong. In this case, it shows the message "Nothing is entered". If we had entered a negative height or width, it would have warned of this, by showing the message that the values are out of the scope of a predefined (min-max) range.

(2) Next to this, the GUI will colour all the nodes, starting from the main node in the data tree leading to node with invalid information, red. In that way the user can always trace back the location of missing or invalid data in the data tree. When all data is correctly entered, all nodes will be black.

3.4 Units

The units associated with an entry box are shown to the right of the box. SealSim 1.1 currently works with SI-Units. In a future version of SealSim 1.1 IP units and a conversion function will be considered.

3.5 Material properties

In the current version of SealSim 1.1 material properties can be a function of time and temperature, and can be attributed a probability distribution. In a future version, when the physical models are extended, material properties could also be explicit functions of other variables, i.e. water exposure and UV exposure. Currently it is assumed that these kinds of effects are accounted for in the time dependency of a specific property. In SealSim 1.1 material properties are extracted from two databases.

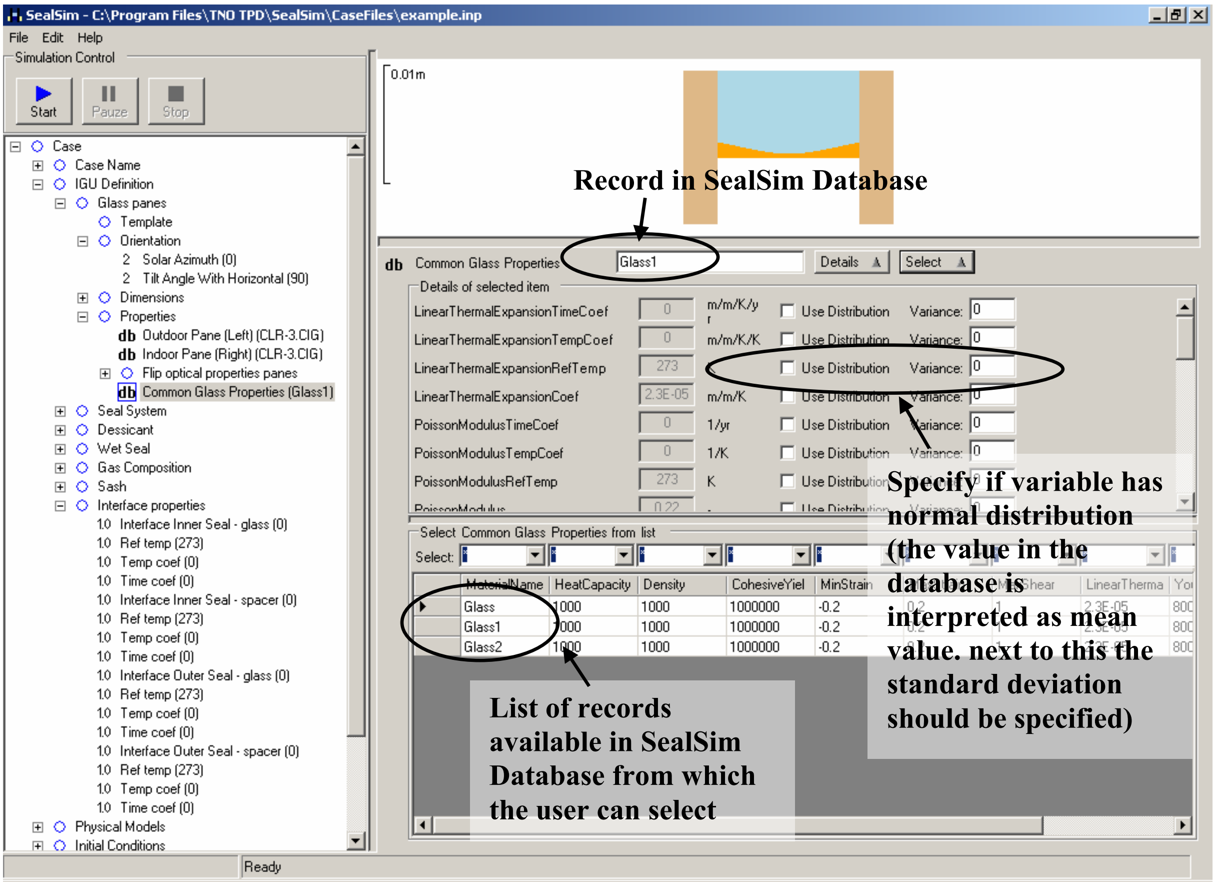


Figure 9 Sample input window belonging to sub node "Glass Properties".

3.5.1 Material property as function of time and/or temperature

In case a material property is a function of time and/or temperature, a value for the temperature coefficient and time coefficient have to be specified, together with a reference temperature, according to the following expression (where T denotes temperature, and t time):

Actual Value (t, T) =Value+TempCoef*(T-RefTemp) +TimeCoef*(t-RefTime)

The temperature is expressed in [°C] or [(degree symbol) K]. The time is expressed in [yr]. The term "(t-Retime)" corresponds to the time that has passed since the start of the simulation. The actual value of the material property is updated during the simulation using this expression.

3.5.2 Material property attributed a probability distribution

All material data can be attributed probability distributions. In the current version of SealSim 1.1 the only supported probability distribution is a normal probability distribution. In a future release this will be extended to include other types of probability distributions, i.e. Weibull. A normal distribution is fully defined by its mean value and standard deviation. In case a material property is attributed a probability distribution, the value as given in the database is interpreted as being the mean value. Next to the mean value, a standard deviation has to be entered. The standard deviation is not stored in the database, but will be stored in the SealSim 1.1 case description file.

Databases referenced by SealSim 1.1

SealSim 1.1 extracts material data from the following two databases:

(1) "GlazingTPD.mdb"
This Database contains the thermal and optical properties of glazing materials (total solar, visible, and thermal infrared optical properties of a glazing as well as the thickness and thermal conductivity). The Glazing Database is identical to the International Glazing Database "Glazing.mdb" (version 13.4, date: 9-9-2003) as used in OPTICS5 and WINDOW5. The only difference is that an extra query (qryTNO-TPDGlazingProp) was added by LBNL especially for SealSim 1.1. Database information can be found on http://windows.lbl.gov/materials/IGDB.

(2) "SealSim.mdb",
The SealSim 1.1 database contains physical properties of the following materials:
- Solid materials
- Polymers
- Gases
- Desiccants

A description of the specific items in the SealSim 1.1 database can be found in the file 'SealSimDataBaseDoc.xls' that is present in the installation directory of the SealSim 1.1 program.

Remarks

- Database values are interpreted as mean values when a probability distribution is attributed.
- The user has full access to the SealSim 1.1 database "SealSim.mdb" via Microsoft ACCESS 2000 WARNING: do not change the materials properties without being able to return to the previous values.
- In the current version of SealSim 1.1 the user cannot modify, delete or add properties or database records of the SealSim 1.1 database "SealSim.mdb" via the GUI.
- Aspen Research Corporation has taken up the task of populating the SealSim 1.1 Database "SealSim.mdb" with some initial values. Additional testing and development work is needed to fully populate all significant data. .
- It is advisable not to change column headings in the SealSim 1.1 Databases that are related to gas properties. In principle the column headings can be renamed, though care has to be taken to also rename the query to the database column heading in the XML file that defines the GUI. The column headings should be identical
- The user has no access to the International Glazing Database.

3.6 Running a simulation, warning & errors

When all nodes, defining the IGU, climate conditions, etc, are entered and accepted by the GUI, a simulation can be started by clicking on the Start button in the simulation control panel. When the start button is pressed, a temporary input case description file is generated, which is redirected to the SealSim 1.1 Engine. If you want to save the case you have to explicitly save it, otherwise upon closing SealSim 1.1 you may loose the information. The SealSim 1.1 Engine reads the temporary input case description file and performs the actual calculation of the IGU behaviour in time. The SealSim 1.1 engine opens in a separate "Command Window", which during runtime also can be viewed for the simulation status. Manual closing this Command Window, thus aborting the Engine, may be dangerous, as contact with the GUI will be lost. The simulation progress is shown in the status bar of the GUI (bottom left), containing amongst other information, the number of Monte Carlo Runs performed so far (percentage). Statistics about the simulation process are logged not only to the Command Window, but also to a log file, called "sls.log" (residing in the Engine directory). It is advisable to always check this log file for warning messages etc, as this can have a huge impact on the results. In case an error occurs, the simulation stops and the log file will be automatically opened. If it fails to do so, manually open the log file, check the error message, and take appropriate action. When the simulation is finished, the Engine stops, and the Command Window will close by itself. Output of the simulation can be viewed in the summary node of the GUI, or by importing output files into Excel for example.

3.7 Saving or opening a case description file or results file

In a similar way, a case description file (*.inp) or results file (*.out) is opened, via the menu "File/Open", you can save a case description file, via the menu "File/Close". When you save a case description file and results, log information also exists for that case, these are saved under the same name (but with a different file extension).

Note:

- Filenames (including directory path) are limited to 100 characters in total.
- A case description file contains all the information about the IGU, needed to run a SealSim 1.1 simulation, such as IGU dimensions, material properties, simulation options, etc. Only climate data actually is not stored in the case description file. For climate data, only the climate data filename and directory location is stored.
- A "case description file" in SealSim 1.1 jargon is also called an "Input file".
- If you made changes to an imported case description file, and exited SealSim 1.1 without saving, the information is lost).
- If you made changes to an imported case description file, performed a simulation run, and exited SealSim 1.1 without saving, the information is also lost. Though if you didn't run another simulation in the meantime, the information might be recovered from the temporary input case description file "sls.inp" that resides in the Engine directory.

3.8 Output not shown in the GUI, which can be visualised with e.g. MS Excel

- The output file (*.out) is used for visualisation in the GUI, but also contains more information than shown in the GUI. For every Monte Carlo run, information is written in this file about failure criteria and user limits, at each time step (or user selected time interval). To view this information, the output file may be imported into, for example, MS Excel (use option “blank delimited input” in Excel).
- The output files (*.out2) and (*.usr) contain additional information pertaining to the user set time interval, which may be also viewed, using MS Excel or a comparable spreadsheet program.
- The file “geom.txt” contains information about the geometry of the IGU, as conceived by SealSim 1.1. It may be viewed by reading into Excel.
- Note: filenames (including directory path) are limited to 100 characters in total.

3.9 Example files

Two SealSim 1.1 input example files are installed when setting up SealSim 1.1. The sole purpose of these two examples is to show the logistics of SealSim 1.1 (e.g. showing a case consisting of more than one Monte Carlo Simulation Run). It does not represent a realistic IGU, subjected to realistic conditions, with realistic material properties and variations in material properties.

The example files can be accessed via the Menu File, Submenu Open. Browse to the subdirectory “Case Files” in the target installation directory of SealSim 1.1 (default C:\Program Files\TNO TPD\SealSim).

4 SealSim 1.1 Program Description

In this chapter the nodes of the SealSim 1.1 data tree will be discussed. Only the most important nodes will be discussed. Data entry boxes belonging to a selected node can be found on the right of the GUI window.

4.1 Node: Case Name

In this mode, the user is required to enter the project name, file creation date and name of the file creator.

4.2 Node: IGU Definition

In this node the IGU is defined. The main nodes of the node “IGU Definition” are shown below.

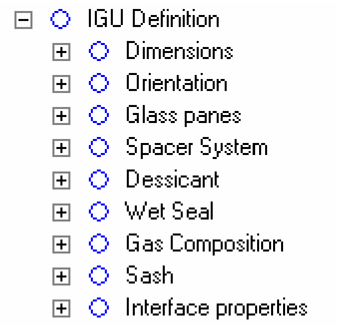


Figure10. The node “IGU Definition”

4.2.1 *Node: IGU Definition/Orientation*

This chapter assumes only the northern hemisphere.

In this node, the orientation of the IGU, azimuth and tilt, have to be entered. The elevation of the IGU is specified via the outdoor climate file, see section 4.5. The orientation of the IGU is important to determine:

- Direction of sun radiation at a certain time
- Gravitational forces
- Wind forces (i.e. to determine which side is leeward or windward)
- Heat transfer coefficients

Azimuth

An azimuth of 0° corresponds with an IGU facing south that, at circa 12 o'clock, each day will receive the most radiation from outside, when located in the northern hemisphere. These values must be revised for proper orientation when working on cases located in the southern hemisphere.

+180 deg orientation N
-135 deg orientation NE
-90 deg orientation E
-45 deg orientation SE
0 deg orientation S
+45 deg orientation SW
+90 deg orientation W
+135 deg orientation NW

Tilt

The tilt angle equals zero when the IGU is in horizontal position and the outer lite is facing straight up into the sky. At 90 degrees the IGU is in vertical position.

Procedure for calculating sun incident angle on IGU

The Incident angle of sun radiation on the window, as function of time and IGU location, is calculated according to the procedure described in the ASHRAE fundamentals handbook 2001, SI edition, Chapter 30. Normal incidence corresponds to 0°. The IGU does not receive any direct sun radiation when the incident angle is outside the range –90° to 90° or when the sky is completely covered by clouds or darkness.

4.2.2 *Node: IGU Definition/Glass lites*

4.2.2.1 *Optical properties of single glazing layers at normal incidence*

In this paragraph the properties of single glazing layers are set (specifically the solar properties) at normal incidence, for the indoor and outdoor lite. The source of the information is the International Glazing Database. The International Glazing Database contains the total solar, visible, and thermal infrared optical properties of a glazing as well as the thickness and thermal conductivity. A Glazing record contains amongst others entries, the following data:

Thickness	Glass thickness Units: mm
Tsol	Solar transmittance of the glazing layer
Rsol1	Solar reflectance of the glazing layer, exterior-facing side
Rsol2	Solar reflectance of the glazing layer, interior-facing side
Tvis	Visible transmittance of the glazing layer
Rvis1	Visible reflectance of the glazing layer, exterior-facing side
Rvis2	Visible reflectance of the glazing layer, interior-facing side
Tir	Thermal infrared (longwave) transmittance of the glazing layer
Emis1	Infrared (long wave) emittance of the glazing layer, exterior-facing side
Emis2	Infrared (long wave) emittance of the glazing layer, interior-facing side
Cond	Conductance of glass Units: W/m-K

4.2.2.2 *"Flip" lite properties*

The user has the possibility to flip the (front-back) solar properties of an individual lite.

4.2.2.3 *Angular dependence of glazing optical properties*

The angular dependence of a sheet of glass is extrapolated from its normal properties by the procedure described in the ASHRAE fundamentals handbook 2001, SI edition, Chapter 30. This extrapolation uses angular data of CLEAR and BRONZE glass as found in ASHRAE 30.22, Table 12.

4.2.2.4 *Optical properties of the Double-Layer Glazing system*

For the determination of the optical properties of the double-glazing system, the procedure followed is described in the ASHRAE fundamentals handbook 2001, SI edition, chapter 30 "multi-layer glazing systems".

4.2.2.5 *Other Glass properties*

In this node, the physical properties of glass not present in the International Glazing Database, such as the structural properties of glass are selected from the SealSim 1.1 database. The selected data is assumed to be applicable for both the indoor and outdoor lites. Note that in this window also, probability distributions can be attributed to the selected glass properties. The structural behaviour of the lites is considered to be linear elastic, where the lites are simply supported plates, subjected to uniform loads, though varying in time. Setting material properties as a function of temperature and time, and attributing probability distributions as discussed in the previous chapter.

Laminates

Note that in this version of SealSim 1.1 the glass lites are considered as monolithic, having monolithic properties. Structural effects of laminates therefore are not considered.

4.2.3 *Node: IGU Definition/Spacer System*

4.2.3.1 *Introduction*

In this node the spacer system is defined, together with the materials it is composed of. Current spacer systems supported by SealSim 1.1 are Thermo Plastic Spacers (TPS) and Box-spacers. They both have in common, an Outer Seal and an Inner Seal, of polymer origin. The Outer Seal sometimes also is referred to as the Secondary or Structural Seal, and the Inner Seal as the Primary or Moisture Vapour Transmission (MVTR) Seal. The reason for this is that the outer seal is selected for its favourable structural properties, in general at the same time showing high vapour transmission rates. The inner seal is selected for its favourable vapour transmission properties, but in general shows poor structural properties. In the case of a TPS system, desiccant is mixed with the inner polymer, which acts as a buffer for water vapour, preventing condensation in the gas space, impairing vision. In the case of a box spacer, desiccant is present in the spacer bar. The polymer material structural behaviour can be identified as "visco-elastic" (combination of spring and dashpot elements), and shows time-history behaviour.

In most cases the inner seal is intact along its perimeter, that is, shows no holes or gaps, that expose the outer seal directly to the gas space of the IGU, and that could form a shortcut for water vapour entering the gas space. However due to the presence of corner keys or due to gas filling, part of the inner seal is missing. In SealSim 1.1 it is possible to enter the total surface area of the missing inner seal. This is specified indirectly by specifying the effective perimeter of the inner seal that is missing. In the gas permeation sub-model of the IGU, a partly missing inner seal is accounted for by solving an extra gas permeation equation for this part of the seal. It is however assumed that the missing section of the inner seal is relatively small, and has no effect on the structural properties of the seal.

4.2.3.2 *Box-spacer & TPS-spacer: parametric setup geometry*

The geometry of the spacer is assumed to be parametric. What this means is that the general layout (mutual relations) of the spacer is predefined, but not its dimensions. The specific dimensions do have to be entered by the user. When entering the dimensions, they have to conform to established rules in order not to violate the predefined layout. If the user does not comply, the SealSim 1.1 engine will detect this, pressing you to enter correct values.

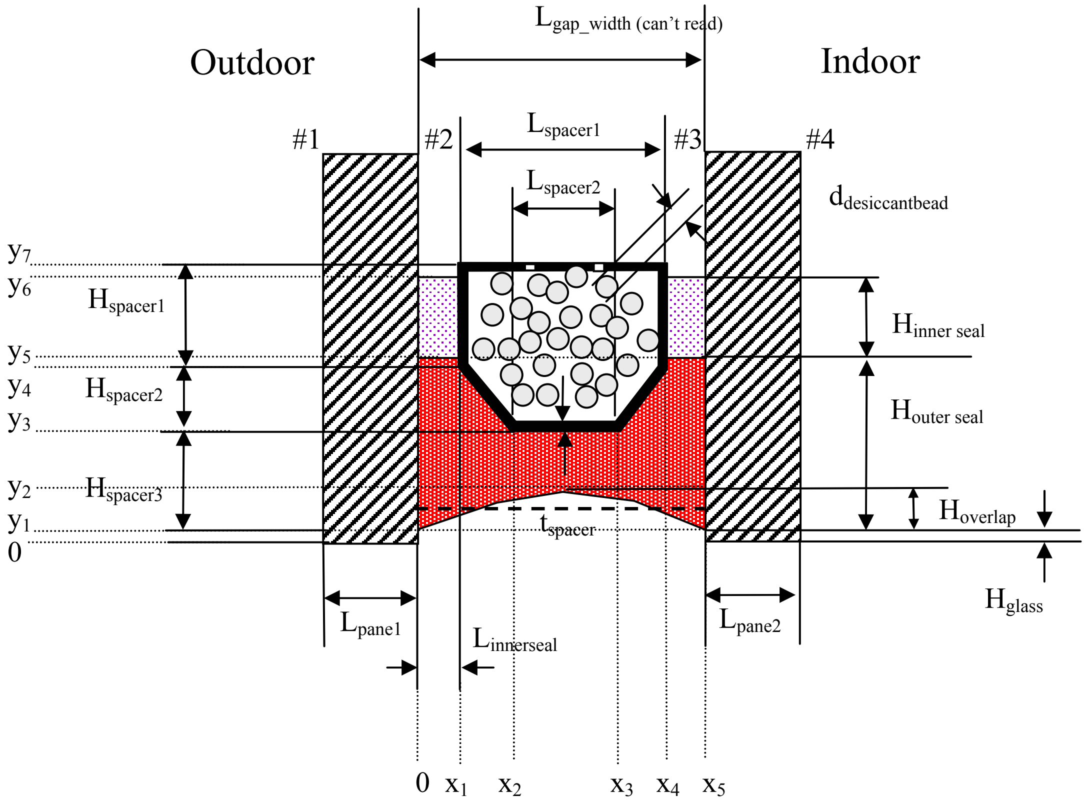


Figure 11, Box-spacer. Parametric setup; the dimensions indicated by an arrow have to be entered by the user.

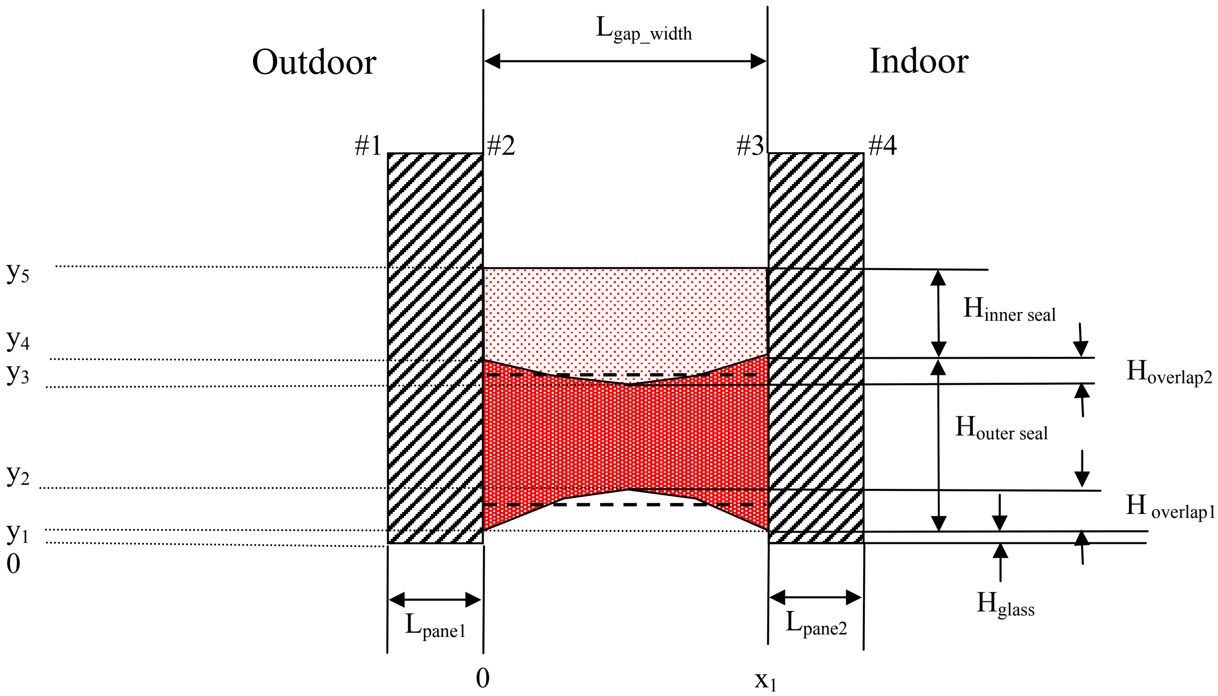


Figure 12, TPS-spacer. Parametric setup; the dimensions indicated by an arrows have to be entered by the user.

Assumptions with regard to parametric setup of the spacer systems:
- The widths between the glass lites are that of an unstressed system.
- The seal is assumed to be positioned exactly in the middle of the two glass lites
- The seal curvature is represented by a circle-segment
- In the internal representation in SealSim 1.1 the curvature is simplified to a flat line, while conserving the cross sectional area of the seals.
- Surface #1 is "outdoors", surface #4 "indoors"

Specifically the TPS-spacer dimensions must comply with the following rules:
- In x-direction: $x_1 > 0$
- In y-direction: $y_5 > y_4 \geq y_3 > y_2 \geq y_1 \geq 0$

Specifically the Box-spacer dimensions must comply with the following rules:
- In x-direction: $x_5 > x_4 \geq x_3 > x_2 \geq x_1 > 0$
- In y-direction: $y_7 \geq y_6 > y_4 \geq y_3 > y_2 \geq y_1 \geq 0$ & $y_6 > y_5 \geq y_3$

4.2.3.3 *Intact Inner and Outer Seal or part Inner Seal missing*

In most cases the inner seal is intact along its perimeter, showing no holes or gaps, which could present a shortcut for water vapour entering the gas space. However due to the presence of corner keys, gas fill holes not plugged adequately, etc., parts of the inner seal may be missing. In SealSim 1.1 this is specified by entering the effective perimeter of the inner seal that is missing. SealSim 1.1 calculates the associated surface area of the missing seal. In the gas permeation sub model of the IGU, parallel gas permeation is calculated through the part of the seal that is intact, and through the part of the seal that is not intact. It is assumed however that the missing section of the inner seal is relatively small, and has no effect on the structural behaviour of the IGU.

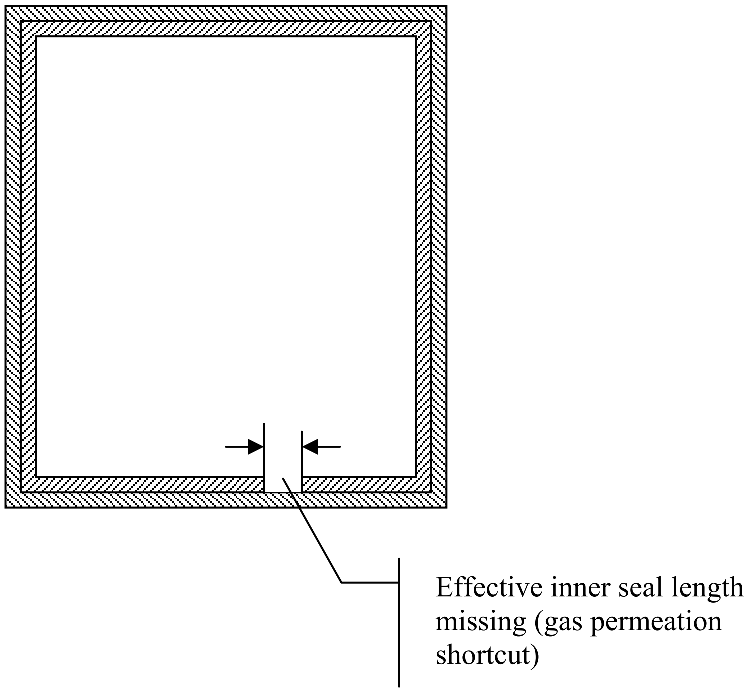


Figure13) Parts or several parts of the IGU inner seal may be missing, forming a shortcut for gas permeation. The associated area is entered in SealSim 1.1 by specifying the effective perimeter of the inner seal that is missing.

4.2.4 *Node: IGU Definition/Gas Composition*

In this node, the initial gas composition, inside and outside the IGU is defined, as well as the composition of gases dissolved in the polymer and absorbed in the desiccant. Note that the gas composition together with the total gas pressure and temperature (defined in the node "Initial Conditions"), define the absolute amount of gas that is present in the gas space, in solution in the polymer or absorbed in the desiccant. Up to 10 gases can be selected in SealSim 1.1, to play a role in gas-permeation. The user is advised to limit the number of gases to a minimum, as computation time will increase with the number of gases selected. At least two gases should be selected. In most cases, water vapour will be selected as a default.

The initial composition has to be specified in mole fractions (equivalent to volume fractions assuming the ideal gas law). If the fractions summed are not unity, the fractions will be scaled to enforce this, using the same scaling factor for all gases. If gases are not selected, their gas fractions will be ignored in the summation. Of all the gases, water vapour is considered to be the only one that is a condensable gas.

For the gas space the composition has to be specified, including the condensable gas (H_2O). It is assumed that initially all H_2O is present in gaseous form. For the Ambient the composition has to be specified, excluding condensable gas (H_2O). Information about the ambient water vapour concentration is obtained from the Climate Data file (relative humidity in combination with temperature). Hence, only the composition of gases other than water vapour has to be specified. Again it is assumed that initially all H_2O is present in gaseous form. For the polymer, the composition of the gases dissolved must be specified, including condensable gas (H_2O). For the desiccant the composition of the gases absorbed must be specified, including condensable gas (H_2O).

4.2.5 *Node: IGU Definition/Wet seal*

The wet seal is the seal between the outside of the IGU and the sash. See Section 4.2.6

4.2.6 *Node: IGU Definition/Sash*

The sash holds the IGU. In this version of SealSim 1.1 it is assumed that the structural behaviour of the sash is comparatively stiff. The thermal displacement of the sash therefore is prescribed as displacements to the wet seals, indirectly loading the IGU. The sash on the outside is assumed to be exposed to the same (outside) climate as the IGU. The sash on the inside is assumed to be exposed to the same (inside) climate as the IGU. Each time step, a thermal balance over the sash is made (1-d conduction). From the resulting linear temperature profile, the sash deformation is calculated, which is a function of time.

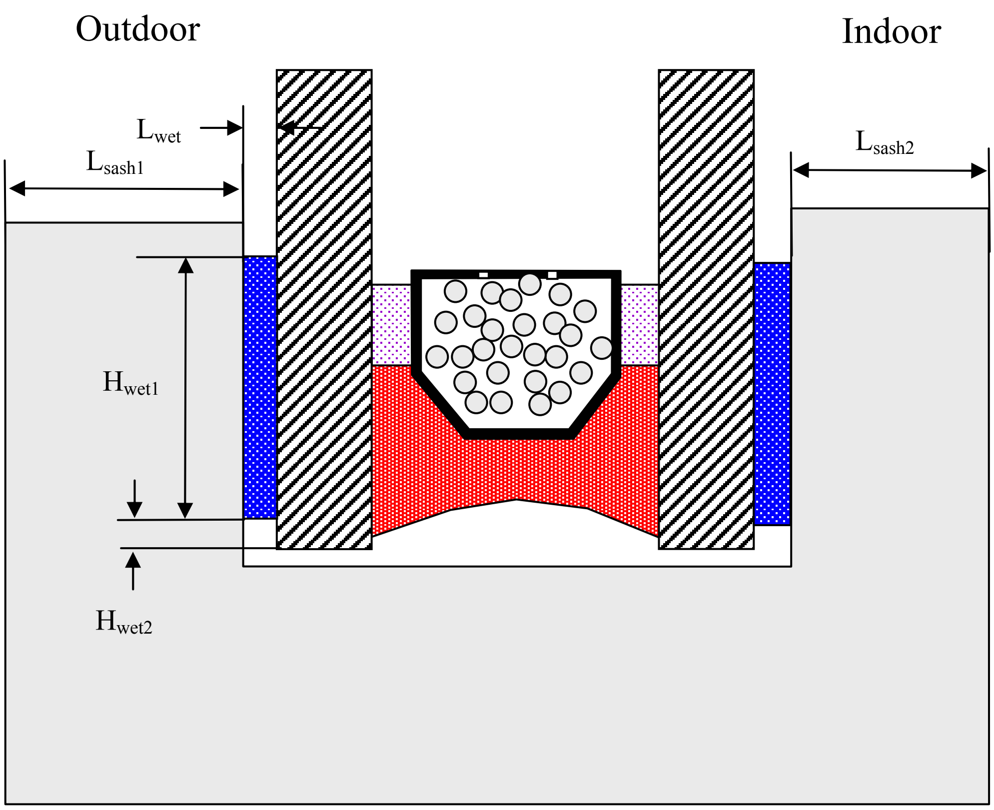


Figure 14, Wet seal and sash. Parametric setup

4.2.7 *Node: IGU Definition/Interface properties*

The adhesion strength of the various interfaces in the system cannot be attributed to a single material. By definition, two materials are involved, as are surface texture, cleanliness of the surfaces, etc. Therefore, adhesion properties are not included in the Materials Database, though in a future release this may become a separate Database record. The adhesion strength is used to calculate at what point in time an interface will fail. At that moment, the IGU is considered to have failed. Loss of adhesion will immediately be followed by water vapour entering the unit, or noble gases being lost from the unit. By attributing probability distributions to the interface properties, manufacturing variations, for example, can be accounted for.

The user has to enter adhesion properties for the following interfaces.

- Inner Seal – Glass
- Outer Seal – Glass
- Inner Seal – Box spacer
- Inner seal – Box spacer

4.3 Node: Physical Models

In this node, the various physical sub models can be activated or deactivated. Details about the physical sub models are documented separately (see also appendix).

Permeation sub model
If the gas permeation model is selected, a (transient) differential equation will be solved for:

- Gas permeation taking place through the intact seal, including absorption/desorption of gases by the seal polymer and (in case of a TPS system) by desiccants that are mixed with the inner seal. For each gas, a 1-dimensional spatial differential equation is solved (for 10 gases 10 equations)
- Parallel gas permeation taking place through the part of the seal where the inner seal is missing. For each gas, a 1-dimensional spatial differential equation is solved (for 10 gases 10 equations)
- Gas absorption/desorption by desiccant beads (in case of a box-spacer) that are present in the spacer bar
- Absolute pressure of the gas space, and gas composition.

Thermal sub model
Currently there is the option to select between two thermal models, both based on ISO 15099

1. SealSim 1.1 version of ISO 15099 routines (temperature.DLL).
2. Official LBNL ISO 15099 routines (w5cog.DLL). These routines are preferred but unfortunately give convergence problems sometimes. A newer version 6 is being worked on by LBNL.

If the thermal model is selected, a calculation will be performed for each time step:

- A “center of glass” of glass calculation is performed; conforming to (ISO 15099), where the gap width of the IGU is taken equal to the average gap width at that moment, giving the temperatures of the gas space and the glass surfaces. For the gas composition the composition at the specific time step is used. Note that non-standard climate data is used to calculate the temperatures and U-factor, climate conditions varying in time as selected by the user are used in the equations.
- The one dimensional temperature distribution in the sash is calculated where the frontal surface area of the frame is taken as the effective surface area for heat transfer.
- For a box-spacer:
  - The spacer bar temperature is taken equal to the gas space temperature
  - The seal temperature towards the interior is taken equal to the average of the gas space temperature and interior glass surface temperature (surface #3).
  - The seal temperature towards the exterior is taken equal to the average of the gas space temperature and exterior glass surface temperature (surface #2)
- For a TPS spacer, the seal temperature is taken equal to the average outdoor glass temperature (surface #2) and the indoor glass lite surface temperature (surface #3).

Structural sub model
If the structural model is selected, a calculation will be performed for each time step:

- The lite deformation is calculated
- The deformation of the inner and outer seals will be calculated, together with the deformation of the wet seals, where the thermal deformations of the sash and spacer bar are imposed as boundary condition to the wet seals. The seals behaviour is visco-elastic (time-history effect).
- Loads on the system are
  - Pressure differences over the gas space,
  - Wind loads (See ASCE 7) (Ref: ASHRAE Fundamentals 2001, chapter 16)

- Thermal expansion/contraction of the spacer bar
- Thermal expansion/contraction of the spacer sash
- Thermal expansion/contraction materials
- Gravitation (watch how this prints out – this should be on previous page)

Material properties
Each time step the material properties are updated according to the defined time dependency and temperature dependency.

Iterative procedure
As the sub models are coupled, i.e. a change in gap width results in a change in temperatures, gas in the gas space contracts/expands, resulting in a change in pressure difference over the lites affecting the gap width etc, an iterative procedure is used to solve the various equations of the sub models. Within a time step, the sub models are called one by one repeatedly, and when new information becomes available about temperatures, pressures, deflections, material properties, etc, the old values are immediately replaced by the latest approximation, until the values do not change anymore per sub iteration. In that case the sub models are considered to be converged, after which SealSim 1.1 will proceed to the next time step in the simulation.

4.3.1 *Node: Physical Models/Specifics Thermal Model*

In this node the seal temperature as calculated by SealSim 1.1 can optionally be overwritten by user defined temperatures, as given in the file (“*.tsl”). The file format used is described below. The first time entry at “0 hour” in this file corresponds to 01 January 00:00 hour, at the user specified base year.

```
!=========================================================
!  Temperature seal as function of time (optional)
!=========================================================
!
!  Description:     Fantasy seal climate
!  Climate period: 1 Jan 2003 -....
!  Location       : nxcbn
!
!  Author         : Han Velthuis TNO-TPD
!  Date           : March 2003
!
!  Nomenclature
!  ------------
!  Time [hr] = Time passed since base date (01 Jan 00:00 hour of user specified base year)
!  Temp [C] = Seal temperature
!
!  Note
!  ----
!  - Lines with starting with '!' are skipped
!  - Data is read line after line starting with dollar sign
!  - There should at least be two time data entries
!  - Table is linearly interpolated
!  - Time data is extrapolated when not available in table!
!
!  Time   Temp
!  [hr]   [C]
$=========================================================
       0d0    20d0
     100d0    20d0
```

Figure15) Example file format

Time “0 hour” in this file corresponds to 01 January 00:00 hour, at the user specified base year.

4.3.2 *Node: Physical Models/ Specifics Structural Model/Wind Loads*

The expression for difference between pressure on the building surface and the local outdoor atmospheric pressure at the same level in an undisturbed wind approaching the building is given by ASCE 7 (ref: See ASHRAE Fundamentals 2001, chapter 16).

$$\Delta p = C_p \cdot \tfrac{1}{2} \rho U_H^2$$

Where C_p= local wind pressure coefficient for the building surface. A distinction is made for the windward or leeward side.

- The local wind speed U_H at the top of the wall in this expression is estimated by applying terrain and height corrections to the hourly speed U_{met} from a nearby meteorological station. U_{met} is generally measured in flat, open terrain.
-

$$U_H = U_{met} \left(\frac{\delta_{met}}{H_{met}} \right)^{a_{met}} \left(\frac{H}{\delta} \right)^{a}$$

The anemometer that records U_{met} is located at a height H_{met}, usually 10 m above ground level. The wind boundary layer thickness δ and exponent for the local building terrain and for the meteorological stations δ_{met} & a_{met}, have to be determined from ASHRAE tables.

4.3.3 *Node: Physical Models/Thermal Model/Film Coefficient*

The indoor film coefficient, the outdoor film coefficient, and film coefficient of the gas space are calculated according to ISO 15099. For the calculation of the outdoor film coefficient the following options are available (for a detailed description see ISO 15099):

0 = ISO 15099
-1= Old ASHRAE SPC142 correlation
-2=Yazdanian-Klems correlation
-3=Kimura correlation

4.4 Node: Initial conditions

In this node the user enters the initial conditions of the IGU, that is, the conditions that apply for the IGU just before simulation start ("time zero"). The simulation starts at a user-defined relative time period since the "climate base date" is manually entered by the user. From that time onwards, the IGU will be subjected to the environmental condition. Simulation start does not necessarily have to correspond to time of manufacturing of the IGU, but could also be time of installation or any other (user-defined) instant.

Thermal model

- With respect to the thermal model, the initial temperature of the IGU (including sash) is assumed to be uniform. The user has to enter the initial temperature.
- The reference temperature for thermal deformations is taken equal to the initial temperature. Hence, the thermal deformation of the IGU is assumed to be zero initially.

Gas permeation

- Gas permeation at time zero is assumed to be zero.

Structural model

- In the node "IGU Definition", the user entered the dimensions of the unstressed IGU.
- The initial conditions are a totally stress free system, the following initial conditions/assumptions/loads are applied to the unit, in order to calculate the deformation of the seals and glass lites that are present initially:
    - Zero thermal deformations.
    - At time zero, with regard to the seals, the viscous part of the visco-elastic effects is assumed to be zero; this represents a no 'history' effect. If one would think of a seal structural element replaced by an equivalent "spring-dashpot" counterpart, the dashpots initially are assumed to be zero.
    - Wind loads are zero.
    - Pressure forces. The user sets values for pressure inside and outside the IGU (the indoor and outdoor pressure are initially assumed equal as a default). The specified pressures are assumed to be the effective pressure for the unit (it is not corrected for elevation, for example).
    - Gravitation forces. At time zero the user can set a gravitation constant deviating from the default value of 9.81 m/s^2 (after time zero, when the simulation starts, the default value takes effect again).
    - For calculation of the gravitation forces, the tilt angle of the unit is important. At time zero the user can set a tilt angle deviating from the default value entered before in the node "IGU Definition/Orientation" (after time zero, when the simulation starts, the default value will take effect again).
    - With the loads described above SealSim 1.1 determines the initial deformation of the lites and seal. Note that up to this point, SealSim 1.1 uses no information out of the climate data files.

Next time step,

Given the initial conditions for the IGU, SealSim 1.1 will start time stepping (if the user presses start on the simulation control panel) to the next time step and so on. When the simulation is started and the time increases from time 'zero' to the first time step, SealSim 1.1 evaluates the climate (boundary) conditions at the first time step, and calculates the response of the IGU as a result of these boundary conditions. All sub models and default gravity and tilt (if selected) will be effective.

4.5 Node: Climate Data

The user has to specify the following climate data as function of time:

- The Outdoor climate (TMY2 format)
- The Indoor climate as a function of time
- The Outdoor climate just outside the seal if different from ambient (Optional)
- The climate repetition period (Optional)

Remarks

- The climate repetition period option is explained in the section dealing with the TMY2 format. When the climate repetition period option is selected, the first part of the climate file is used for every repetition
- When the climate repetition period option is selected, it applies to all the climate files mentioned above.
- The data in the climate files is assumed to start at 00:00 hours at the user defined base date, which is 01 Jan, 00 at the user defined base year. The link to an absolute date is required in order for SealSim 1.1 to calculate the sun incident angle of the IGU for each time step.

4.5.1 *Node: Climate Data/Outdoor Climate (TMY2 format)*

Introduction
SealSim 1.1 supports the Typical Meteorological Year (TMY2) data format for the outdoor climate. Note that it is important to distinguish between the *contents* of the data-set (actual climate-data) and the way the data is entered, that is, the *format*. In the future more data formats will be supported.

The official TMY2s data file on the very first line contains the meteorological station information (station identification ID, location, time zone and elevation), followed by "typical" hourly climate data for a 1-year period. So if the behaviour of an IGU in New York City were to be studied, exposed to "typical" weather data, it would be natural to import the official climate data file for the meteorological station of New York City (94728.tm2). If you are not satisfied with "typical" data, but you think conditions are worse or even better, you can use your own climate data file (this option will be explained later) as long it is in the correct format.

The official TMY2 data files contain "typical" climate values for one year, and therefore are not linked to any absolute year. It only assumes that climate data starts 01 January 0:00 hour. The data in the climate file is assumed to start at 00:00 hour on the user defined base date, which is 01 Jan, 00 on the 01 (first) day and the 0.00 hour of the user defined base year. The user will be asked to link the climate data to an absolute date, in order for SealSim 1.1 to calculate sun incident angle at the IGU for each time step.

SealSim 1.1 recognizes TMY2 files by their file extension "tm2", for example a valid TMY2 climate data file name could be "user.tm2". Of climate data, only the climate data filename and directory location is stored in the case description file ('*.inp'), not the climate values.

Where to get official TMY2 data?
The user can freely download the official TMY2 climate data set of cities throughout the US (http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/). The TMY2 data sets and manual were produced by the National Renewable Energy Laboratory's (NREL's) and are funded and monitored by the U.S. Department of Energy's Office of Solar Energy Conversion.

Write your own climate data file
Alternatively, the user may write his/her personal TMY2 climate data set, as long as it is written into the TMY2 format (see website described before), or in the SealSim 1.1 extension of the TMY2 format as described in the next paragraph, which also accepts non-hourly data (that is increments smaller or larger than one hour).

Validity of the climate data
SealSim 1.1 does not check the validity of the climate data; this is the responsibility of the user. SealSim 1.1 only assumes that the appropriate columns in the climate data file are filled with numerical data in the correct format. SealSim 1.1 also does not perform a validity check on month or day number specified in the climate data file, as it internally calculates with time steps expressed in terms of hours passed since 01 Jan 00:00, the default base date. The climate data is linked to solar position (see above) by date.

4.5.2 TMY2 *Data Columns currently used by SealSim 1.1*

On the first line
- Meteorological Station ID
- Latitude
- Longitude
- Time zone
- Elevation

Second line and subsequent lines:
- Time
- Dry Bulb Temperature
- Relative Humidity
- Barometric Pressure
- Wind speed
- Wind direction
- Direct Normal Radiation
- Total sky cover

4.5.3 *Baseyear and basedate*

The official TMY2s data sets contain typical climate values for one year, and are not linked to an absolute year in time. It only assumes that climate data starts 01 January 0:00 hour AM (local standard time). In order for SealSim 1.1 to know at what time it has to pick data pick out of the file, the user has to link the climate data to an absolute year, which is defined as the “base year”. The climate data starts January 1st at 00:00 hour AM at the user-defined baseyear. This is called the “base date”. Climate data is assumed to be present in the TMY2 data file from this date on. Hence, the 1st hourly TMY2 climate data entry has attributes month=01, day=01 and hour=01 as the associated climate information is in principle valid for the whole prevailing hour. See comments on previous page.

By default, SealSim 1.1 looks up the climate data using the one hour ***increments,*** in the TMY2 climate data file, passed since the basedate. If the file is longer than one year (SealSim 1.1 extension) SealSim 1.1 will just continue reading data, taking into account leap years when calculating the associated date (in terms of day, month, year, hour). A normal year contains 8760 hours, and a leap year 8784 hours.

4.5.4 *SealSim 1.1 extension of the TMY2 data format*

4.5.4.1 *Climate data extending more than one year or repeated patterns*

The official TMY2s data sets contain hourly climate data values for a 1-year period, starting from 1 January 00:00 hour AM (local standard time). Optionally the user may specify climate data for shorter periods less than a year, or periods longer than 1 year. This can be done by deleting or adding lines, or making use of the climate repetition period option:

- The user can concatenate (official or user-defined) TMY2 data sets into a large file, for example covering more than one year. Note that information is allowed only on the very first line of the climate data-file station; so delete superfluous station information that may become sandwiched in-between while concatenating TMY2 files. The number of lines present in the thus created file (minus the very first line with station information) will be equivalent to the number of hours of climate data contained in the file.
- If the “climate” repeat period option is selected, and the repeat period is for example set to “168 hours” (equivalent to 1 week), the first 168 hours of climate data is used over and over when looking up climate data (fictitiously the first 168 hours worth of data in the climate file is concatenated indefinitely). The time at which data is looked-up in the climate data file is related to the simulation time by the expression (where all times are in hours or fractions of hours, and the simulation time equals the numbers of hours since the baseyear 01 January 00:00 hour)

$$Time_{lookup} = \text{MODULO (Simulation time, Climate repeat period)}$$

An example is given below:

The 'base date' e.g. is 1990 01 January 00:00 hour AM (local standard time).
Climate repeat period e.g. 168 hours (equivalent to one week)

The simulation time e.g. is 1990 02 January 12:00 hour = 60 hours since basedate
The climate lookup time MOD (60, 168) = 60 hours since base date
1990 02 January 15:00 hour

The simulation time e.g. is 1990 09 January 12:00 hour = 168+60 hours since basedate
The climate lookup time MOD (228, 168) = 60 hours since base date
1990 02 January 15:00 hour

The simulation time e.g. is 1990 30 January 15:00 hour = 735 hours since basedate
The climate lookup time MOD (735, 168) = 63 hours since basedate
1990 02 January 15:00 hour

Non-hourly Climate data & solar data

If the user specifies a negative value in character positions (2:3) in the *first* TMY2 climate data line entry, SealSim 1.1 will interpret character positions (4:9) as the absolute number of hours passed January 01 00:00 hour (local standard time) (for the whole file). These character positions are normally reserved for month, day and hour information. This option is very handy for example when the climate conditions are constant or vary linearly over extended periods of time. In that case the climate data can be made very small in size.

Note: In the TMY2 format, solar data by default the flux arriving at a surface during the past one hour [Wh/m^2]. In case of non-hourly data, when specifying the solar flux at a certain point in time, it should be written as the amount received during the past one hour. For example, if two subsequent data entries have to be specified in the climate data file that lie 3 hours apart, and at the first time (associated with the first data entry) the solar flux is 600 W/m^2, and 800 W/m^2 3 hours later, the two subsequent values entered in the climate data file are 600 Wh/m^2, and 800 Wh/m^2.

4.5.5 *Interpolation/extrapolation of climate data*

Note that if SealSim 1.1 tries to look up climate data in the TMY2 file at a point between two times at which climate data is present, SealSim 1.1 will use linear interpolation. If SealSim 1.1 tries to lookup climate data at a point in time before data is present in the file, SealSim 1.1 will not generate an error, but will lookup the first climate data entry found (which is in the basedate). If SealSim 1.1 tries to lookup climate data at a point in time beyond which data is present in the climate file, SealSim 1.1 will not generate an error message, but will use the last climate data entry found.

Example: the climate data file contains 2 data entries, one at Jan 01 1990 00:00 hour and the second one at Jan 13 1990 22:00 hour. Now if, for example, SealSim 1.1 tries to lookup data in the climate data file on Aug 23, 1963 23:45 hour, it will effectively use climate data from Jan 01 1990 00:00 hour. Now if, for example, SealSim 1.1 tries to lookup data in the climate data file on Aug 23, 2063 23:45 hour, it will effectively use climate data from Jan 13 1990 22:00 hour. Now if, for example, SealSim 1.1 tries to lookup data in the climate data file on Jan 04, 1990 13:45 hour, it will use linear interpolation between climate data values given on Jan 01 1990 00:00 hour and Jan 13 1990 22:00 hour.

4.5.6 *IGU-elevation other than Meteorological Station Elevation*

The default IGU elevation is given by the Meteorological Station elevation, as is specified on the very first line in the TMY2 data file. To account for different elevations that the IGU can have in time (for example during transport from the manufacturing location to the storage location and from the storage location to the final location, which may not coincide with the elevation of the nearest Meteorological Station), the user can specify on character positions (143:146) of the TMY2 data file, the actual IGU elevation [m]. If elevation data is present on these character positions, this is interpreted as the actual IGU elevation, taking precedence over the Meteorological Station elevation. If these character positions are blank (default), the IGU elevation is taken as equal to the Meteorological Station elevation. In the case of non-hourly data the procedure is similar. The IGU elevation is derived from values at the identified column, if present.

- The barometric pressure in the data file is valid only at the Meteorological Station elevation and not at the IGU elevation. To convert the barometric pressure information of the Meteorological Station to barometric pressure at the user defined elevation, SealSim 1.1 must convert the pressure at the Meteorological Station elevation to the pressure at the IGU elevation. For this SealSim 1.1 uses the barometric expression (ASHRAE Handbook 2001, Fundamentals 6.1) which gives the barometric pressure as function of the height:

  p = pref * (1-2.25577E-5*z)^5.2559

4.5.7 *Node: Climate Data/Indoor Climate*

In the file “*.ind” the indoor climate is defined, using the format described below. In the calculation of the film coefficient according to ISO 15099, wind speed is not used. The column should be completely filled with numerical data, to prevent a read error. The first time entry at “0 hour” in this file corresponds to 01 January 00:00 hour, at the user specified base year. The link to an absolute date is required in order for SealSim 1.1 to calculate sun incident angle at the IGU as function of time. When a climate repetition period option is set, as explained in the section dealing with the TMY2 format, this input applies to this file.

```
!=========================================================
!  Indoor climate as function of time
!=========================================================
!
!  Description    : Fantasy indoor climate
!  Climate period : 1 Jan 2003 - ....
!  Location       : nxcbn
!
!  Author         : Han Velthuis TNO-TPD
!  Date           : March 2003
!
!  Nomenclature
!  ------------
!  Time [hr] = Time passed since base date (01 Jan 00:00 hour of user specified base year)
!  Temp [C]  = Air temperature
!  RH   [%]  = Air relative humidity
!  Trad [C]  = Radiation temperature indoor
!  Wind speed [m/s] = Indoor wind speed
!
!  Note
!  ----
!  - Lines with starting with '!' are skipped
!  - Data is read line after line starting with dollar sign
!  - There should at least be two time data entries
!  - Table is linearly interpolated
!  - Time data is extrapolated when not available in table
!
!---------------------------------------------------------
!  Time   Temp   RH    Trad  Wind speed
!
!  [hr]   [C]    [%]   [C]   [m/s]
$=========================================================
       0d0    20d0   30d0  40d0    5d0
       1d0    22d0   33d0  45d0    5d0
```

Figure16. Example file format

4.5.8 *Node: Climate Data/Outdoor Climate Seal*

In this node the ambient climate just outside the seal ("*.csl") is specified, if deviating from the outdoor climate of the unit. The file format used is described below. The first time entry at "0 hour" in this file corresponds to 01 January 00:00 hour, at the user specified base year. The link to an absolute date is required in order for SealSim 1.1 to calculate sun incident angle at the IGU as a function of time. When a climate repetition period option is set, as explained in the section dealing with the TMY2 format, this input applies to this file.

```
!========================================================
! Outdoor climate for seal (optional)
!========================================================
!
!  Description    : Fantasy climate just outside seal
!  Climate period : 1 Jan 2003 - ....
!  Location       : nxcbn
!
!  Author         : Han Velthuis TNO-TPD
!  Date           : March 2003
!
!  Nomenclature
!  ------------
!  Time [hr] = Time passed since base date (01 Jan 00:00 hour of user specified base year)
!  Temp [C]  = Air temperature
!  RH   [%]  = Air relative humidity
!
!  Note
!  ----
!  - Lines with starting with '!' are skipped
!  - Data is read line after line starting with dollar sign
!  - There should at least be two time data entries
!  - Table is linearly interpolated
!  - Time data is extrapolated when not available in table !
!
!  Time   Temp   RH    (note 20C&100RH=2338 Pa)
!  [hr]   [C]    [%]
$========================================================
       0d0    20d0   50d0
       1d0    20d0   50d0
```

Figure17. Example file format

4.6 Node: Time Settings

In this node the following time information is set

- Simulation time period, by entering the simulation start date and time, and stop date and time (local standard time).
- The numerical time step. This is the time increment SealSim 1.1 uses to step in time, through the simulation time period
- Print interval. This is the time interval at which SealSim 1.1 writes information about a time step to file. If a negative number is entered, this is interpreted as the total number of printouts over the simulation time period, equidistantly spaced over the simulation time period.
- Extra refinement of the time step, at simulation start up. The actual time step used by SealSim 1.1 will be the specified number of time steps divided by this number.

Each time step:

- Climate boundary conditions are determined (from the climate files) to which the IGU will be exposed during that time step.
- The physical sub models are called after each other repeatedly and material properties are updated in between, etc, until all temperatures, pressures and deflections are converged for that time step.
- Failure criteria will be determined (if these are a function of time and temperature) and checked against user set limits. If a failure occurs, this particular simulation (Monte Carlo Run) will stop, and SealSim 1.1 will proceed to the next Monte Carlo Run. If no failure occurred at this time step, the simulation will proceed to the next time step.
- Data is written to file at a user selected time interval.

Note:

- In order to resolve fine details in the climate data files, the time step should be set accordingly small.
- When the numerical time step is set to a small value this is favourable for the stability of the convergence process, but this is detrimental for the computation time.
- At start up there is the possibility to use extra-refined time steps, in order to account for large changes in boundary conditions the IGU is exposed to.

Important warning with regard to date format and regional settings computer

- SealSim 1.1 assumes the date format to be DD/MM/YYYY (day/month/year), that is, European date format. If the settings of your computer are United States (or other), setting of the simulation start and stop date and time via the GUI with the help of the calendar reverses the order of the date format to (internally) MM/DD/YYYY, giving unexpected results. To resolve this, change your computer date settings (temporarily) to European. Choose e.g.: English (United Kingdom) in the Regional Settings page of the Control Panel of your computer. The GUI needs to be restarted after the Regional Setting has been changed to resolve this conflict. Fixing this problem is planned for a future version of SealSim 1.1.

4.7 Node: Fail Criteria Durability

In this node the user enters which failure criteria are active together with the failure limit. Every time step is checked to determine whether one of the failure limits is exceeded by the IGU. If a failure occurs, the failure ID (identification) will be recorded together with the time of failure. If the IGU does not fail within the simulation time period, the failure ID will be given the value zero, denoting that no failure occurred during the simulation time period and that the IGU has passed. The table below gives a list of failure ID's implemented currently that can be activated individually.

After all predefined numbers of Monte Carlo Runs Simulation Runs are ready; a summary of the information is presented. It contains information about the Durability Index, the predicted average lifetime or lower bound for the average lifetime, frequency of failures that could be attributed to a certain failure ID, and time to failure associated with a particular failure ID, etc.

ID	Description
0	No Failure
1	Dew point gas space exceeds user set limit
2	Condensation on outdoor lite (outdoor surface)
3	Condensation on outdoor lite (gas-space surface)
4	Condensation on indoor lite (gas-space surface)
5	Condensation on indoor lite (indoor surface)
6	Heat transfer coefficient exceeds user set limit (Instantaneous heat transfer coefficient in absence of solar radiation)
7	Gas loss #1 exceeds user set limit
8	Gas loss #2 exceeds user set limit
9	Gas loss #3 exceeds user set limit
10	Gas loss #4 exceeds user set limit
11	Gas loss #5 exceeds user set limit
12	Gas loss #6 exceeds user set limit
13	Gas loss #7 exceeds user set limit
14	Gas loss #8 exceeds user set limit
15	Gas loss #9 exceeds user set limit
16	Gas loss #10 exceeds user set limit
17	Desiccant water load exceeds user set fraction of theoretical maximum
18	Deflection outdoor lite exceeds user set limit
19	Deflection indoor lite exceeds user set limit
20	Distance between lites in centre points drops below user set limit
21	Average distance between lites drops below user set limit
22	Effective cohesive stress Inner Seal exceeds limit
23	Obsolete
24	Obsolete
25	Effective cohesive stress Outer Seal exceeds limit
26	Obsolete
27	Obsolete
28	Obsolete
29	Stress outdoor lite exceeds limit
30	Stress indoor lite exceeds limit
31	Adhesive stress interface (inner seal <==> glass) exceeds user set limit
32	Adhesive stress interface (inner seal <==> spacer) exceeds user set limit
33	Adhesive stress interface (outer seal <==> glass) exceeds user set limit
34	Adhesive stress interface (outer seal <==> spacer) exceeds user set limit
35	Tensile strain inner seal exceeds limit

36	Shear inner seal exceeds limit
37	Tensile strain outer seal exceeds limit
38	Shear outer seal exceeds limit
39	Compressive strain inner seal exceeds limit
40	Compressive strain outer seal exceeds limit
41	Tensile strain wet seal (outdoor) exceeds limit
42	Tensile strain wet seal (indoor) exceeds limit
43	Compressive strain wet seal (outdoor) exceeds limit
44	Compressive strain wet seal (indoor) exceeds limit

Table1. List of failure ID's with short description that can be activated individually.

Note

- **Glass lite deflection**
  Deflection is expressed in [m]. Zero deflection means that glass lites are perfectly flat. The deflection is calculated in the centre of the lite.
- **Distance between glass lites**
  The distance is expressed in [m] and is calculated as the distance between the indoor and outdoor lite.
- **Definition effective stress**
  For the determination of stress failure of the seal components (visco-elastic polymer), the effective Hubert-Hencky stress [N/m^2] is used (combination of normal stress and shear stress) according to (see also chapter Physical Models):

$$\sigma_{eff} = \sqrt{\sigma_{normal}^2 + 3\tau^2} .$$

Note obsolete failure criteria

Be sure to never activate the obsolete failure criteria given in Table 1. Some of the failure criteria are not defined yet and are therefore indicated as obsolete. The obsolete failure criteria where used for debugging purposes of the SealSim 1.1 GUI-Engine connection, data transfer and visualisation. If an obsolete failure criteria is selected, an artificial failure is generated at time "1.6 * simulation time period" with a standard deviation of "0.5 * simulation time period".

Note desiccant loading

Desiccant loading with water is not only a function of temperature of the desiccant and the partial pressure of water vapour, but also of the partial pressures of other gases present, who compete with each other to occupy 'vacant absorption sites'. The theoretical maximum loading at a certain temperature is defined as the loading of water by the desiccant, if water vapour would be the only gas present, in the limit of high water vapour pressure. The theoretical loading capacity with water therefore is a function of temperature, which in general varies during the simulation time period.

4.8 Node: Simulation Control

Monte Carlo Simulation Runs
As already explained before, a complete SealSim 1.1 Simulation Run, consists of one or more Monte Carlo Simulation Runs. The user can specify the number of Monte Carlo Simulation Runs. The number of Monte Carlo Simulation Runs that are necessary to obtain statistical relevant output is up to the user to determine. In general the more variables attributed to a probability distribution, the more Monte Carlo Runs will be required. For linear models, the number of Monte Carlo Runs necessary to obtain a defined accuracy can be determined prior to running a SealSim 1.1 simulation, as explained in the Appendix. For non-linear problems, as is the case for the IGU, the number of runs cannot be determined beforehand. Even afterwards, after analysing the data obtained so far, it is difficult to determine how many additional Monte Carlo Runs are necessary to arrive at the requested accuracy. Therefore the user is urged to attribute as few probability distributions to variables as possible. If there are no probability distributions attributed, and all variables defining the IGU system do have fixed definite values, there is no sense in making more than one simulation run. SealSim 1.1 will detect this automatically, and SealSim 1.1 will perform just one run.

Iterative procedure
As the physical sub models are coupled, i.e. a change in gap width results in a change in temperatures, gas in the gas space contracts/expands, resulting in a change in pressure difference over the lites, affecting the gap width etc, an iterative procedure is used to solve the various equations of the sub models. Within a time step, the sub models are called one by one repeatedly, and when new information becomes available about temperatures, pressures, deflections, material properties, etc, the old values are immediately replaced by the latest guess, until the values do not change between sub-iterations. In that case the sub models are considered to be converged, after which SealSim 1.1 will proceed to the next time step in the simulation.

With respect to the numerics of time stepping; an implicit time stepping procedure is used (backwards in time) and not an explicit procedure such as Euler (forward in time). The advantage of implicit time steps is that there are no constraints that have to be considered about the size of the numerical time step, for numerical stability reasons. However, the accuracy of the solution will be a function of the size of the time step (as will be computation time).

What are residuals?
The changes in values between sub-iterations in a time step, i.e. of temperature, are called “residuals”. The user can specify the (associated) error norm on which SealSim 1.1 will decide if a certain time step is converged, together with the maximum number of sub-iterations per time step in which the sub models have to be converged. If the error norm is set very strict, in general the simulation will be more accurate, but it will take more sub-iteration per time step to converge. *The user should always check if the results of the simulation are sensitive to the user set error norm!* If the results are sensitive, the user should set the error norm even stricter, and rerun the simulation, and check the results again.

To make things even more complicated, within a sub model in general, an iterative procedure is used to produce a new guess. The user can also specify the maximum number of iterations per sub model. So a distinction should be made between “sub model iterations” and “sub-iterations per time step”.

What are relaxation factors?
Setting so-called relaxation factors may influence the speed, at which the equations converge. As already mentioned, within a time step, the sub models are called one by one repeatedly, and when new information becomes available about temperatures, pressures, deflections, material properties, etc, the old values are immediately replaced by the latest guess, until the values do not change anymore between sub-iteration. In that case the sub models are considered to be converged, after which SealSim 1.1 will proceed to the next time step in the simulation. When the variables are updated, the old values

are replaced with the latest guess. If the latest guess differs significantly from the old value, this may lead to convergence problems in the sub models that use this latest information. The update process may be dampened, by replacing the old temperature not with the latest guess, but a value in between the old value and latest guess, according to the following expression (for temperature):

$$Value_{new} = Value_{old} + f * (Value_{latest\_guess} - Value_{old})$$

The weighing factor "f" is called the relaxation factor. The relaxation factor "f" ranges between 0 and 1. If the relaxation factor, f=0, the updated value equals the old value, and effectively nothing changes. If the relaxation factor, f=1, the updated value equals the latest guess. If "f" is taken in between 0 and 1, the new updated value consists of a weighted average between the old temperature and the latest guess.

If the residuals of the equations oscillate between sub-iterations or even diverge, using a lower relaxation factor may help, though it may take more iterations to converge and thus longer computer time. Note that when the relaxation factor is put equal to zero, the variables do not change and the convergence process may be satisfied (an error might occur in the convergence process seeming to indicate convergence has occurred when in fact it has not). *The user should always check if the relaxation factors are set to a very small value or zero, as the outcome of the simulations cannot be trusted anymore!*

5 Number of Monte Carlo Runs to obtain statistical relevant output

Question
Can I say a priori, before actually running a SealSim 1.1 simulation, how many Monte Carlo Simulations Runs (denoted 'm') must be run, in order to obtain a statistically relevant output, and in which way the number of runs is related to the number of variables (denoted 'n') that have Normal distributions.

Answer
Yes, if the output is a linear function of the input variables (which is not the case for SealSim 1.1) and, the variables are mutually independent, in practice no.

Questions
If 'No', how do I then determine if the output is statistical relevant?

Answer
In that case, the simplest thing to do is to run a couple of simulations, analyze the results, and assuming that the outcome is Normally distributed, determine how many additional simulation runs have to be performed, to obtain the accuracy you desire. If a simulation has more than one output, the most critical result will dictate the total number of simulation results.

Uncertainty limits for a linear combination of independent variables

A measurement (or simulation) response is based on a number of n variables $x_1\ x_2 \dots\ x_n$, which are mutually independent and identically distributed with a Normal distribution with mean value μ_x and standard deviation σ_x.

The measurement (or in our case simulation) response is a linear combination of the $x_1\ x_2 \dots$ xn:

$$F = a_1 \cdot x_1 + a_2 \cdot x_2 + \dots + a_n \cdot x_n$$

Then the statistical distribution of F is also Normal, with mean μ_F and standard deviation σ_F. Under the assumptions mentioned above, the mean and standard deviation of F are related to the mean and standard deviation of the integral of x-variables:

$$\mu_F = \mu_x \cdot \sum_{i=1}^{n} a_i \quad \text{and} \quad \sigma_F = \sigma_x \cdot \sqrt{\sum_{i=1}^{n} a_i^2}$$

When the measurement is performed m times, the average value of the resulting $F_1\ F_2 \dots F_m$ can be obtained. The statistical distribution of this average value is also Normal with mean value $\mu_{F\ aver}$ and standard deviation $\sigma_{F\ aver}$ where

$$\mu_{F\ aver} = \mu_F \quad \text{and} \quad \sigma_{F\ aver} = \sigma_F / \sqrt{m}$$

From a sample of m measurement values the mean value and standard deviation of F can be calculated. The actual values of the mean and standard deviation are within specified uncertainty limits. These uncertainty limits depend on:

- The number of measurements: the limits are narrower with higher values of m

- The reliability that is required: the limits are wider when they must be founded with higher reliability

In the figures below the uncertainty limits for the mean value and standard deviation are given for various values of m and the reliability.

*In figure 1 uncertainty limits are given for the mean value relative to the actual standard deviation σ_F of the measurement variable. The limits should be applied to both sides of the measured mean value.

* The figures should be re-numbered starting with Figure 18 because there are 17 un-numbered figures in the manual to this point. Failure to number all figures leads to potential confusion. For example, if I am referring to the 1st figure in a discussion to resolve a problem with the software or my SealSim 1.1 simulation, am I talking about the figure on pp 3 or pp 58?

As an example:
For m=5 one obtains at the vertical axes the value 0.6 for the 80% line. This means: when 5 measurements F_1 F_2 ... F_5 are performed, with a confidence of 80% it can be stated that the actual mean μ_F will lie within an interval of $0.6 \cdot \sigma_F$ ($=0.6 \cdot \sigma_{F\,aver} \cdot \sqrt{m}$) at both sides of the measured mean μ_{Faver}.

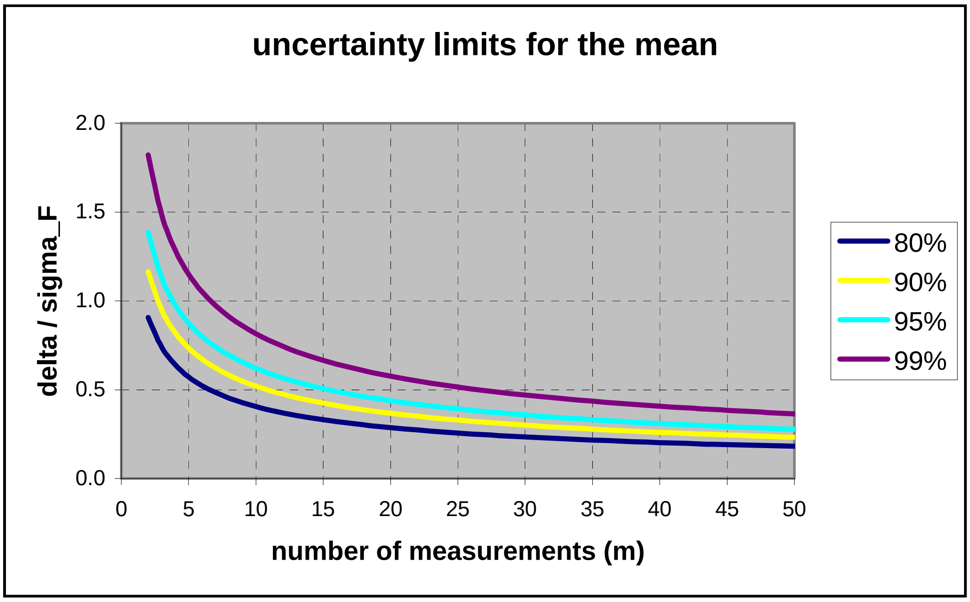


Figure 1

In the figures 2 to 4 the same uncertainty limits are given, but now relative to the actual standard deviation σ_x of the underlying x-variables. This is handy if one beforehand knows something about 'x'. In these figures the relation is also dependent on n (the number of x-variables) and on the coefficients a_1 a_2 … a_n. Limits are calculated for n = 3, 10 and 20, assuming the special case that the coefficients a_1 a_2 … a_n all are equal to 1.

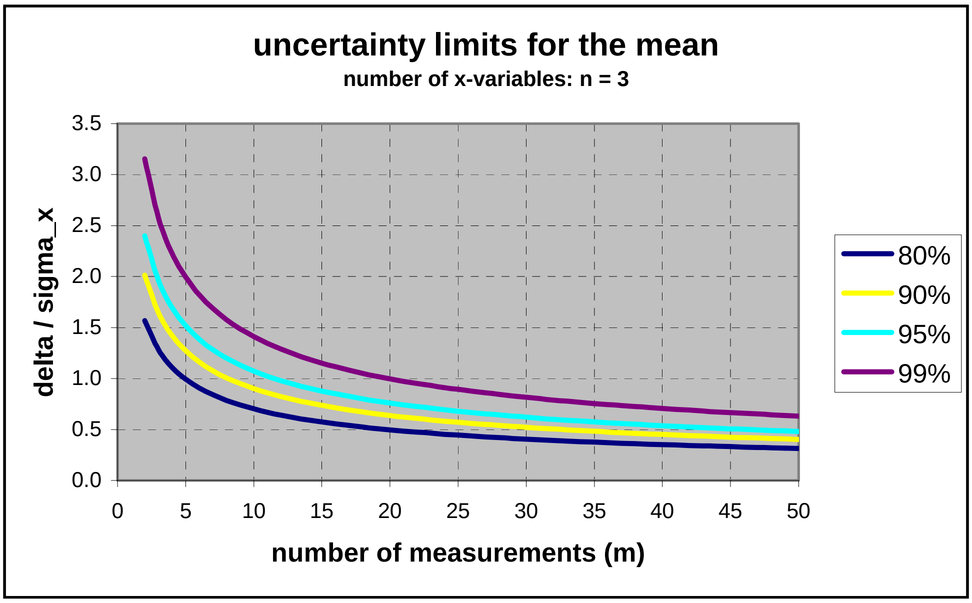


Figure 2

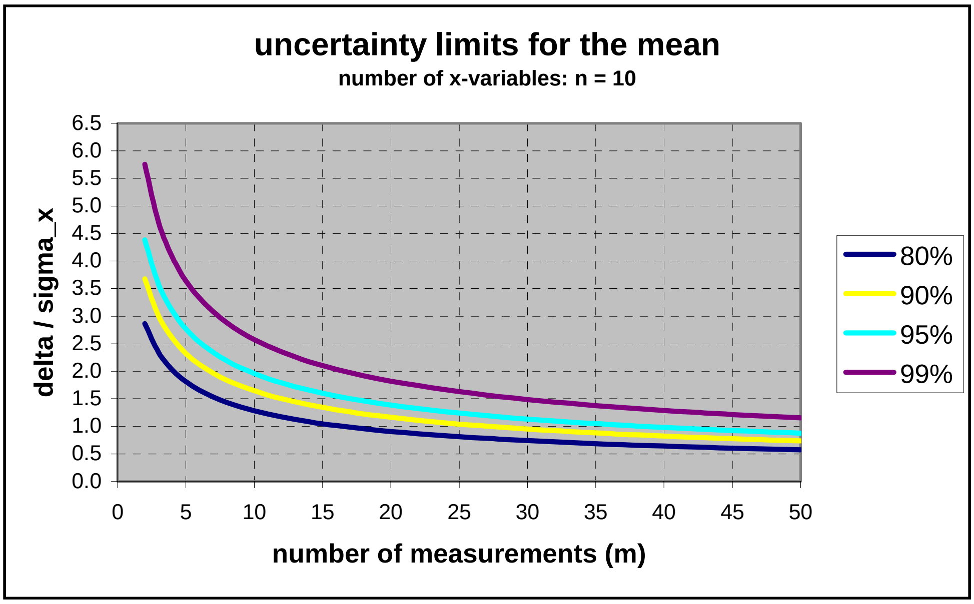


Figure 3

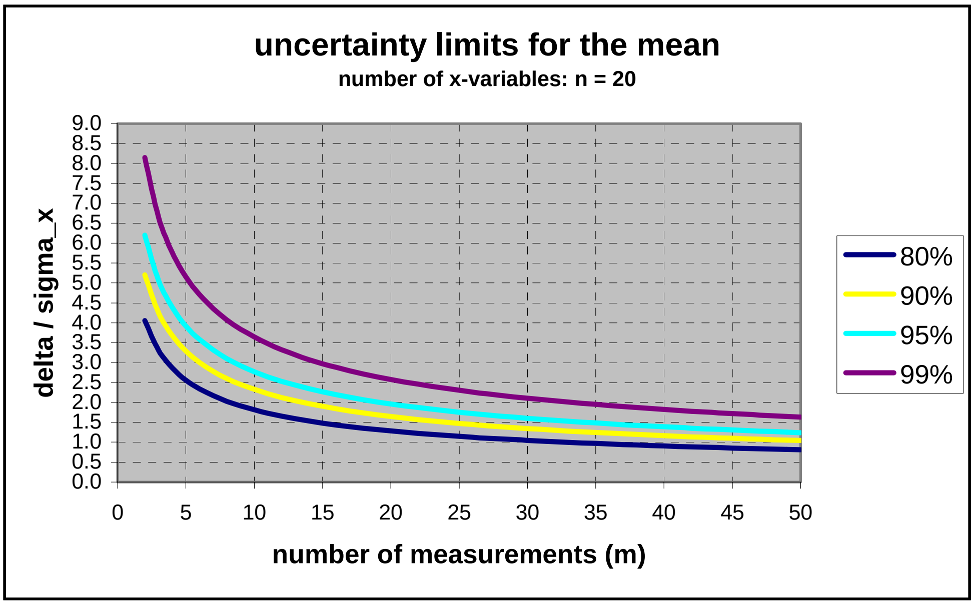


Figure 4

In figure 5 uncertainty limits are given for the actual standard deviation 'sigma' in relation to the measured standard deviation 's'.

As an example:
When m = 5, measurements F_1 F_2 … F_5 are performed, the sample standard deviation's' can be calculated. The black line for 80% shows for m=5 the values 0.7 and 2.0 on the vertical scale. This means that with 80% confidence the actual standard deviation of F (named σ_F) will be between approximately 0.7 and 2.0 times the sample standard deviation 's'.

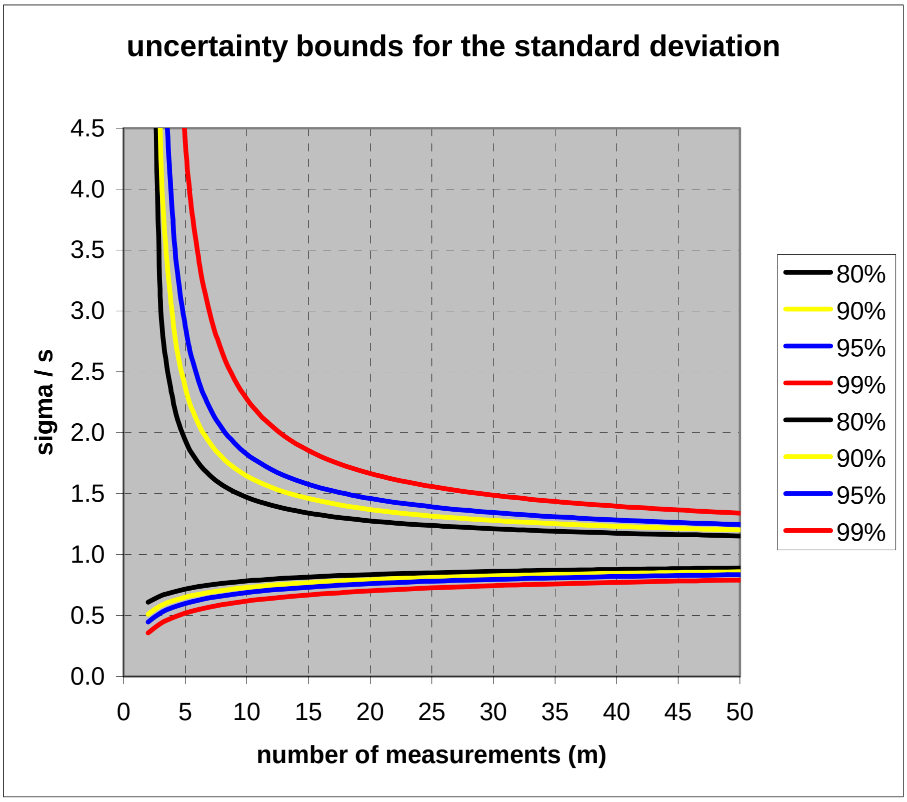


Figure 5

6 Known bugs SealSim 1.1

- If you exit SealSim 1.1, and the Engine is still running, the Engine will not be closed. Close it manually or close SealSim 1.1 via the Menu.
- If SealSim 1.1 files are accessed by another application, and SealSim 1.1 also tries to get access, SealSim 1.1 may give an error. Therefore be sure to close all SealSim 1.1 files before running a SealSim 1.1 simulation.
- In the problem definition file, input variables are specified together with their values, where the order of the input variables in the file is not relevant. If an input variable is present more than once, the value of the last one prevails. However in counting the number of variables that do have a distribution applied, this is not accounted for. Hence more variables with distributions are identified then are really present. However, this has no effect on the simulations or the results.
- The GUI detects if lines in the input file are missing (this only occurs when the input file is corrupted). However if this input file is read into the GUI over a previous input file that does have these lines, these lines are substituted for the missing lines, though these lines are not saved to file. By saving the input file and reading it again, any missing lines can be detected. This bug will only occur when the input file is corrupted. Normally a valid input file is read, consisting of a complete set of lines.
- The picture of the box-spacer and TPS-spacer in the GUI sometimes becomes corrupted, when the computer platform is other than XP. The cause is thought to be the current .NET Framework version 1. The .Net Framework version 2 (when available) is said not to have this problem.
- GUI: renaming or adding/deleting the items of the main tree structure generates an error. Adding/deleting the items in the lower tree structure gives no error.
- In some occasions the Engine tries to access the output file ‘sls.out’ while it is still occupied by the GUI, generating a file access error by the engine.
- Filenames (including directory path) are limited to 100 characters

7 Terminology

Bulk Density
Granulated or powdered material in a container expressed in mass per volume of the container

Climate base date
Defined as January 1st at 00:00 hour am (local standard time) of a user-defined base year; Climate data is assumed to be available in the climate files from this date on. If data is not present, either interpolation is used, or the nearest value taken when out of bounds.

Density desiccant in spacer, bulk density
Typically 39-47 g/linear meter spacer, for 12 mm spacer, will give a bulk density of 270-330 [kg des/m^3 desiccant].

Density desiccant in polymer-desiccant mixture
[kg desiccant/m^3 (superscript) desiccant], for example can be calculated from polymer volume, weight fraction desiccant, and volume mixture. In general it will be higher than bulk or tap density. Typically tap density for zeolite is circa 660-720 [kg/m3], is circa 270-360 [kg/m^3].

Gas space
Gas space between glass lites, also referred to as ‘cavity’

Numerical time-step
On discrete time-steps, balance equations are solved giving information about temperatures, permeation and stresses/deformation at this time-step, taking into account history information and environmental conditions. Taking small time-steps gives an accurate solution in time, but requires long computation times. Taking large time-steps gives less accurate solutions and can even cause numerical instabilities. In the ideal case the solution should not change significantly when halving the time-step. Typically the time-step should be smaller than characteristic changes in climate conditions and characteristic time-constants associated with temperature, permeation and stresses/deformation effects, which depend on the problem. As climate data is given on an hourly basis, a time-step smaller than one hour seems appropriate to resolve details.

Surfaces
Surface #1 of lite 1 is towards the outside of the building. Surface #4 of lite 2 is towards the inside of the building.

Simulation start
The simulation starts in time at a user-defined relative time period from the “climate base date”. From that time onwards, the IGU will be subjected to the environmental condition. The state of the IGU at simulation start is defined by the initial conditions. Simulation start does not necessarily have to correspond to time of manufacturing of the IGU, but could also be time of installation or any other (user-defined) instant.

Simulation stop
The simulation stops in time at a user-defined relative time period since simulation start

Solubility

The solubility of gas in polymer material is defined as: c=S/P where c is concentration, P pressure and D solubility. The units of S depend on units of c and P.

Some options for the units of solubility:
(1) With c given as [kg gas/kg polymer] and P [Pa], then S [kg gas/kg polymer / Pa].
(2) With c [m3 STP / m3 polymer] and P [Pa], then S [m3 STP / m3 polymer / Pa].
(3) With c [kg / m3 polymer] and P [Pa], then S [kg / m3 polymer / Pa].

SealSim 1.1 follows option (3). STP Refers to Standard Temperature and Pressure 0°C, 1 atm (=101325.024 Pa).

Surfaces

Surface #1 of lite 1 is towards the outside of the building. Surface #4 of lite 2 is towards the inside of the building.

Tap Density

The density of a granulated or powdered material when the volume receptacle is tapped or vibrated under specified conditions while being loaded. Each particle of a solid material has the same true density after grinding, milling or processing, but the material occupies more geometric space. In other words, the geometric density is less... approaching 50% less than true density if the particles are spherical.
Handling or vibration of powdered material causes the smaller particles to work their way into the spaces between the larger particles. The geometric space occupied by the powder decreases and its density increases. Ultimately no further natural particle packing can be measured without the addition of pressure. Maximum particle packing is achieved. Under controlled conditions of tap rate, tap force (fall) and cylinder diameter, the condition of maximum packing efficiency is highly reproducible. This tap density measurement is formalized in the British Pharmacopoeia method for Apparent Volume, ISO 787/11 and ASTM standard test methods B527, D1464 and D4781 for tap density.

True Density

The true density of powders often differs from that of the bulk material because the process of comminution, or grinding, will change the crystal structure near the surface of each particle and therefore the density of each particle in a powder. In addition, voids at the surface of a particle, into which liquids will not penetrate, can generate apparent volume, which will cause serious errors when density is measured by liquid displacement. Pycnometers are specifically designed to measure the true volume of solid materials by employing Archimedes' principle of fluid (gas) displacement and the technique of gas expansion. True densities are measured using helium gas since it will penetrate every surface flaw down to about one Angstrom, thereby enabling the measurement of powder volumes with great accuracy. The measurement of density by helium displacement often can reveal the presence of impurities and occluded pores, which cannot be determined by any other method

Width air space

Width of the air space between the lites of glass; In case the glass lites are deformed, the average gap width is used in the thermal calculations (centre of glass U-value)

8 Physical sub models in SealSim 1.1

8.1 Introduction

This chapter describes the physical sub models in SealSim 1.1.

8.2 Permeation sub model

Permeation sub model

If the gas permeation model is selected, a (transient) differential equation will be solved for:

- Gas permeation taking place through the intact seal, including absorption/desorption of gases by the seal polymer and (in case of a TPS system) by desiccants that are mixed with the inner seal. For each gas, a 1-dimensional spatial differential equation is solved (for 10 gases, 10 equations)
- Parallel gas permeation taking place through the part of the seal where the inner seal is missing. For each gas, a 1-dimensional spatial differential equation is solved (for 10 gases 10 equations)
- Gas absorption/desorption by desiccant beads (in case of a box-spacer) that are present in the spacer bar,
- Absolute pressure of the gas space, and gas composition.

Gas diffusion in time though seal polymer mixed with desiccant

8.2.1 Diffusion equation for multiple gases in a polymer matrix mixed with desiccant

The diffusion of gases through polymer material is assumed to be governed by the absorption/desorption mechanism described below.

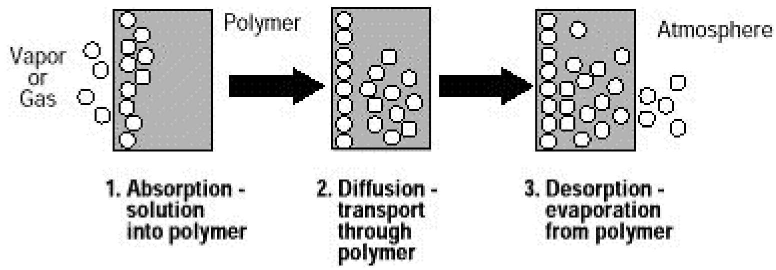


Figure 23, Permeation of gas through polymer via absorption/desorption mechanism

The general equation for one-dimensional spatial, time dependent gas diffusion through a polymer slab, mixed with desiccant is given by:

$$v_p \frac{d\,c_{p,i}}{dt} + (1 - v_p) \cdot \frac{d\,c_{d,i}}{dt} = \frac{v_p}{\tau} \cdot \frac{d}{dx}\left(D \cdot \frac{dc_{p,i}}{dx} \right)$$

Desiccant is assumed to be an immobilising agent for permeation.
If no desiccant is present, the diffusion equation simplifies to:

$$\frac{d\,c_{p,i}}{dt} = \frac{1}{\tau} \cdot \frac{d}{dx}\left(D \cdot \frac{dc_{p,i}}{dx} \right)$$

Where 't' denotes time, and 'x' the distance through the seal in the diffusion direction, the index 'i' denotes the specific gas involved; so when 'n' gases are involved 'n' similar differential equations have to be solved.
The volume fraction of polymer in a mixture of polymer and desiccant is defined as:

$$v_p [m^3 \ polymer/m^3 \ mixture]$$

The polymer - desiccant mixture is assumed to be homogeneously mixed.
The desiccant fraction is given by:

$$v_d = (1 - v_p)$$

The concentration of gas 'i' in solution in the polymer material is assumed to be proportional to the (partial) gas pressure 'p_i ' of gas 'i' [Pa] according to Henry's law:

$$c_{p,i} = S_i \cdot p_i \quad [kg \ gas_i /m^3 \ polymer]$$

Where ‘S_i ’ is the solubility of gas ‘i’ in the polymer material according to:

$$S_i \quad [kg\ gas_i/m^3\ polymer/Pa]$$

The permeation coefficient ‘P_i’ of gas ‘i’ in the polymer is defined by:

$$P_i = D_i \cdot S_i \ \ [\frac{m^2}{s} \frac{kg\ gas_i}{m^3\ \ polymer} \cdot \frac{1}{Pa}]$$

Where ‘D_i' is the diffusion coefficient of gas ‘i’ in the polymer

$$D_i \quad [m^2/s]$$

For simplicity it is assumed that the solubility, diffusion coefficients and permeation constants of the gases are independent of each other. The concentration of gas absorbed by the desiccant is given by a Langmuir sorption isotherm, in the case of a single gas:

$$c_d = c_{\max} \frac{b \cdot p}{1 + b \cdot p} \quad [kg\ gas_i/m^3\ \ desiccant]$$

The factor ‘b’ [1/Pa] determines the shape of the Langmuir sorption isotherm. Note that if ‘b’ is small the concentration becomes proportional to pressure. In this case the concentration is given in somewhat different units:

$$c'_d = \ [kg\ gas_i/kg\ desiccant]$$

Then the definitions of the concentrations can be expressed as follows:

$$c_d = \ \rho_d \cdot c'_d$$

Where the desiccant density is given by:

$$\rho_d = \ [kg\ desiccant\ /\ m^3\ \ desiccant]$$

The absorption of multiple gases by the desiccant is assumed to be governed by the (LRC) Loading Ratio Correlation, an extension of the Langmuir isotherm for a single gas according to:

$$c_{a,i} = c_{\max,i} \frac{b_i \cdot p_i}{1 + \sum_{all\ gases} b_i \cdot p_i} \quad [kg\ gas_i/m^3\ \ desiccant]$$

Solubility, diffusivity and Langmuir shape factor are assumed to be exponential functions of temperature [K] according to:

$$S = S_0 \cdot e^{S_c/T}$$
$$D = D_0 \cdot e^{D_c/T}$$
$$b = b_0 \cdot e^{b_c/T}$$

From the definition of permeability, it follows that the permeability is also an exponential function of temperature:

$$P = P_0 \cdot e^{P_c/T} \quad where \quad P_0 = D_0 \cdot S_0 \quad and \quad P_C = D_c + S_c$$

The desiccant in the polymer matrix acts in general as an immobilising agent, increasing the distance over which diffusion takes place in the polymer. This increase in length is assumed to be a linear function of the amount of desiccant in the polymer matrix, according to:

$$\tau = 1 + \tau_0 \cdot v_d \ \ [m/m]$$

Resulting diffusion equation in terms of pressure
Inserting the definitions in the diffusion equation, gives a diffusion equation in terms of partial pressure. For gas 'i' the expression reads:

$$v_p \frac{d\, S_i \cdot p_i}{dt} + (1 - v_p) \cdot \frac{d\left(c_{\max,i} \dfrac{b_i \cdot p_i}{1 + \sum\limits_{all\ gases} b_i \cdot p_i} \right)}{dt} = \frac{v_p}{1 + \tau_0 \cdot (1\text{-}v_d)} \cdot \frac{d}{dx}\left(D \cdot \frac{dS_i \cdot p_i}{dx} \right)$$

Where

$$S_i = S_{0,i} \cdot e^{S_{c,i}/T}$$

$$D_i = D_{0,i} \cdot e^{D_{c,i}/T}$$

$$b_i = b_{0,i} \cdot e^{b_{c,i}/T}$$

$$P_i = P_{0,i} \cdot e^{P_{c,i}/T} \quad where \quad P_{0,i} = D_{0,i} \cdot S_{0,i} \quad and \quad P_{C,i} = D_{c,i} + S_{c,i}$$

So when, for example, '10' gases are involved in permeation '10' similar differential equations have to be solved in terms of partial pressures of the gases, with as a complicating factor that the equations are interdependent (coupled) via the summation term over all gases in the expression for the LRC Langmuir sorption isotherm.

Initial conditions and boundary conditions
When solving the differential equations, the partial pressures of the gases, on either side of the polymer slab, are assumed to be given. These boundary conditions may vary in time. The initial partial pressures at time zero (simulation start) of gases dissolved in the polymer and absorbed by the desiccant, are assumed to be given by the user. Either the partial gas pressures must be entered or the total gas pressure in combination with the gas composition has to be entered by the user.

Numerics
The equations are discretised spatially using a finite volume formulation in conserved form. The equations are discretised backward in time, avoiding restrictions for the numerical time step in order to enhance numerical stability. The discretised coupled equations are solved by a gauss iteration process.

Example discretisation of the diffusion equation
Now we replace the diffusion equation, for simplicity we use the equation for a single gas:

$$v_p \frac{d\, c_d}{dt} + (1 - v_p) \cdot \frac{d\, c_a}{dt} = \frac{v_p}{\tau} \cdot \frac{d}{dx}\left(D \cdot \frac{dc_a}{dx} \right)$$

By its discretised counterpart; we take for example a small section 'Δx' of the polymer slab, having dimensions 'Δy' and 'Δz' in the other directions, according to the figure below:

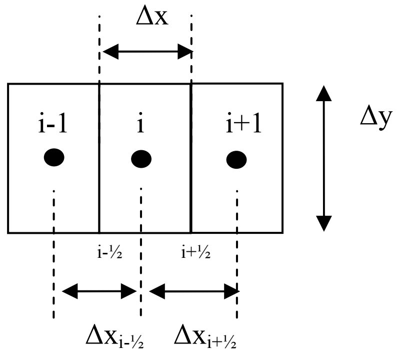


Figure 24, Discretisation of the diffusion equation, control volume with nodes

The index 'i' now refers to the location of the grid node or interface position between control volumes. The index '0' denotes a value the previous time t_0, the index '1' denotes a variable at the current time t_1. The discrete time step is denoted by 'Δt'. Filling in the discretisation gives:

$$\left[v_p \frac{c^1_{p,i} - c^0_{p,i}}{\Delta t} + (1 - v_p) \cdot \frac{c^1_{d,i} - c^0_{d,i}}{\Delta t}\right] \cdot \Delta y \cdot \Delta y \cdot \Delta z = \frac{v_p}{\tau} \cdot \left(D_{i-\frac{1}{2}} \cdot \frac{c^1_{p,i-1} - c^1_{p,i}}{\Delta x_{i-\frac{1}{2}}} - D_{i+\frac{1}{2}} \cdot \frac{c^1_{p,i+1} - c^1_{p,i}}{\Delta x_{i+\frac{1}{2}}} \right) \cdot \Delta y \cdot \Delta z$$

So for every grid node 'i', a discretised equation is obtained. The permeation flux over a volume interface 'i-½' is given by:

$$\phi_{i-\frac{1}{2}} = \frac{v_p}{\tau} \cdot \left(D_{i-\frac{1}{2}} \cdot \frac{c^1_{p,i} - c^1_{p,i-1}}{\Delta x_{i-\frac{1}{2}}} \right) \cdot \Delta y \cdot \Delta z \quad [kg\ gas / s]$$

Conversion expressions from volume fractions to mass fractions and vice versa
Assume we have mass polymer M_p [kg] and volume polymer V_p [m3].
Assume we have mass desiccant M_d [kg] and volume desiccant V_d [m3].

The density of the polymer and of the desiccant is:

$$\rho_p = \frac{M_p}{V_p}$$

$$\rho_d = \frac{M_d}{V_d}$$

Now we mix the polymer and desiccant. The mass fraction and volume fraction polymer is:

$$m_p = \frac{M_p}{M_p + M_d} = \frac{\rho_p \cdot v_p}{\rho_p \cdot v_p + \rho_d \cdot (1 - v_p)}$$

$$v_p = \frac{V_p}{V_p + V_d} = \frac{\frac{m_p}{\rho_p}}{\frac{m_p}{\rho_p} + \frac{1 - m_p}{\rho_d}}$$

8.3 Diffusion in zeolite beads (Box-spacer)

Zeolite is present in pellets (beads) in the gas space (spacer bar). Zeolite does have micro pores (typical size of Zeolite cages is in the order of a molecule diameter; that is a few Å). It is assumed that the pellets do have (macroscopic) tortuous pores, with typical pore diameter of 1 mu. In general, mass transport of gases in the pellets occurs by two mechanisms (1) ordinary diffusion and (2) Knudsen diffusion. Ordinary diffusion, as described by Fick's law, dominates when the pores are large and the gas relatively dense. However when the pores are small and/or the gas density low, the molecules collide with the pore walls more frequently than with each other, and diffusion of molecules along the pore wall is described by the equations of free molecules or Knudsen flow. We assume that predominantly Knudsen diffusion takes place. The effective diffusion coefficient thus is written as:

$$D_{eff} = \frac{\Psi}{\tau} D_{Kn}$$

Where Ψ is the porosity or volume void fraction of the pellet, and τ is the tortuosity factor that accounts for the increased diffusion length due to the tortuous path of real pores, and for the effect of constrictions and dead pores. The Knudsen diffusion coefficient for species 'i' is given by

$$D_{Kn} = \frac{1}{3} d_{eff} c_{av}$$

Where d_{eff} is the effective pore diameter; the factor c_{av} is the average molecular speed of species 'i'

$$c_{av} = \sqrt{\frac{8\Re T}{\pi M_i}}$$

Where 'R' is the universal gas constant, 'T' absolute temperature in Kelvin, and 'M_i' is the molecular weight of species 'i'; we assume that mass transfer in the pellet is the limiting factor The mass balance for a bead reads, using a lumped approach, neglecting accumulation effects in the void relative to zeolite adsorption:

$$\rho_d \cdot V \cdot \frac{d(c_{a,i})}{dt} = A_{eff} \cdot D_{eff} \cdot \frac{M_i}{\Re T} \cdot \frac{\left(p_{i,gas\,space} - p_i\right)}{\frac{d_{bead}}{2}} \text{ [kg species i/s]}$$

Where 'V' is the bead volume (assumed to be spherical), ρ_d the desiccant bead density, and A_{eff} the effective area for diffusion (the average bead surface area is taken $4/3\pi r^2$). The characteristic diffusion length has been taken as half the bead diameter d_{bead}. The right hand side of this expression denotes the flux of species 'i' from the gas space to the desiccant. Desiccant absorption is again described by the Langmuir Loading Ratio Correlation sorption isotherm for multiple species (Einstein notation), described before:

$$c_{a,i} = \frac{c_{i,\max} \cdot b_i}{1 + \sum_{all\ gases} b_i \cdot p_i}$$

Note entering tortuosity in SealSim 1.1

In SealSim 1.1 the tortuosity factor τ cannot be entered, however this can be compensated for by entering for the porosity Ψ of the pellet not the actual value for the porosity, but the porosity divided by the tortuosity.

8.4 Expression for gas space pressure (mass balance gas space)

The gas space is assumed to be well mixed, and of homogeneous composition, which may vary in time. A mass balance of the gas space now reads, for gas 'i':

$$\frac{d(\rho_{g,i} \cdot V)}{dt} = \phi_i \;\; [kg\ gas\ 'i'/s]$$

Where a positive value for 'Φ_i' denotes the net flux of gas 'i' travelling towards the gas space from the seals and/or desiccant beads in the spacer; so if '10' gases are present '10' mass balance equations are apply. We assume that the partial density of gas 'i' is given by the perfect gas law:

$$\rho_{g,i} = \frac{p_i \cdot M_i}{R \cdot T}$$

The expression for the mass balance now can be written as:

$$\frac{d(\frac{p_i \cdot M_i}{R \cdot T} \cdot V)}{dt} = \phi_i \;\; [kg\ gas\ 'i'/s]$$

The gas space volume and temperature can be functions of time, as well as the flux of gas 'i'. Backwards discretising in time gives:

$$\frac{(\frac{p_i^1 \cdot M_i}{R \cdot T^1} \cdot V^1 - \frac{p_i^0 \cdot M_i}{R \cdot T^0} \cdot V^0)}{\Delta t} = \phi_i^1$$

Where the index '0' denotes a value at the previous time t_0, the index '1' denotes a variable at the current time t_1. The discrete time step is denoted by 'Δt'. The gas flux towards the gas space is considered to be given by the permeation model, the temperatures at the current and previous time step by the thermal model, and the gas space volume at the current and previous time step by the structural model. The mass balance now results in an expression for the evolvement of the gas space pressure in time.

The total pressure in the gas space at any time is given by the sum of the partial gas pressures:

$$p_{tot} = \sum_{all\ gases} p_i$$

The gas composition of the gas space in terms of mole fractions (equivalent to volume fraction) is given by:

$$c_i = \frac{p_i}{\sum_{all\ gases} p_i} = \frac{p_i}{p_{tot}}$$

The average mol weight of gases in the gas space is given by:

$$M = \frac{\sum_{all\ gases} p_i \cdot M_i}{\sum_{all\ gases} p_i}$$

The initial partial pressures of gases at time zero (simulation start) in the gas space, are assumed to be given by the user. Either the partial gas pressures have to be entered or the total gas pressure in combination with the gas composition has to be entered by the user.

8.5 Thermal model

If the thermal model is selected, for each time step:

- The sun incident angle on the IGU is determined
- The long wave optical properties of the individual coated or uncoated sheets of the double glazing unit are extrapolated from values available at normal incidence from the glazing database.
- The long wave optical properties of the double glazing unit are calculated at the sun incident angle.
- A "center of glass" calculation is performed; conforming to (ISO 15099), where the gap width of the IGU is taken equal to the average gap width at that moment, given the temperatures of the gas space and the lite surfaces. For the current gas composition, the composition at the specific time step is used. Note that non-standard climate data is used to calculate the temperatures and U-factor, based on climate conditions varying in time as selected by the user.
- The one dimensional temperature distribution in the sash is calculated, similar to ISO 15099, where the frontal surface area of the frame is taken as the effective surface area for heat transfer.
- For a box-spacer:
    - The spacer bar temperature is taken equal to the gas space temperature
    - The seal temperature towards the indoors is taken equal to the average of the gas space temperature and indoor lite surface temperature (surface #3).
    - The seal temperature towards the outdoors is taken equal to the average of the gas space temperature and outdoors lite surface temperature (surface #2)
- For a TPS spacer, the seal temperature is taken equal to the average outdoors lite temperature (surface #2) and the indoor lite surface temperature (surface #3).

8.5.1 Procedure for calculating sun incident angle on IGU

The Incident angle of sun radiation on the window as a function of time and IGU location is calculated according to the procedure described in the ASHRAE fundamentals handbook 2001, SI edition, Chapter 30. Normal incidence corresponds to 0°. The IGU does not receive any direct sun radiation when the incident angle is outside the range –90° to 90° or when the sky is completely covered.

The total solar radiation incident on an inclined surface consists of radiation from a direct (beam), the sky diffuse solar radiation (e.g. reflected from clouds, and scattered radiation) and the ground-reflected radiation, also assumed to be diffuse. All calculations involving solar radiation are based on solar time.

Solar Time is based on the apparent angular motion of the sun across the sky with solar noon the time that the sun crosses the meridian of the observer. Local standard time (LST) is converted to solar time as follows. First, there is a constant correction for the difference in longitude between the location and the meridian on which the local time is based (Eastern, 75 deg W; Central 90 deg W; Mountain 105 deg W; Pacific 120 deg W; Hawaii-Alaska 150 deg W). Note that one degree in longitude is equivalent to 4 minutes (since 360 degrees is one day). Another correction is the equation of time, ET, which takes into account changes in the earth's rotation.

The apparent solar time AST is given by

$$AST = LST + ET + 4\,(LSM - LON)$$

Where ET = Equation of Time, minutes
LST = Local Standard Time
LSM = Local Standard Time Meridian, degrees
LON = Local Longitude, degree
4 minutes of time required for a 1 degree rotation of the earth

$$ET(n) := \left(9.87\cdot\sin\left(4\cdot\pi\cdot\frac{n-81}{364}\right) - 7.53\cdot\cos\left(2\cdot\pi\cdot\frac{n-81}{364}\right) \ldots + 1.5\cdot\sin\left(2\cdot\pi\cdot\frac{n-81}{364}\right)\right)\cdot\text{mi}$$

Where n = day of year (1 - 365)

Solar Geometry: The position of the sun and the geometric relationships between a plane and the beam solar radiation incident on it may be described in terms of the following angles:

L, latitude, is equal to the angle of the location relative to the equator; North is positive.

δ, declination, is equal to the angular position of the sun at solar noon with respect to the equatorial plane (varies from -23.45 to 23.45 degrees).

α, solar altitude, is equal to the angle between the sun's rays and the horizontal (between 0 and 90 degrees).

z, zenith angle, is equal to the angle between the sun's rays and the vertical.

ϕ, solar azimuth, is equal to the angle between the horizontal projection of the sun's rays from due south (positive in the afternoon).

γ, surface solar azimuth, is equal to the angle between the projections of the sun's rays and of the normal to the surface on the horizontal plane.

ψ, surface azimuth, is equal to the angle between the projection of the normal to the surface on a horizontal plane and due south (east is negative).

β, tilt (slope), is equal to the angle between the surface and the horizontal (0 - 180 degrees).

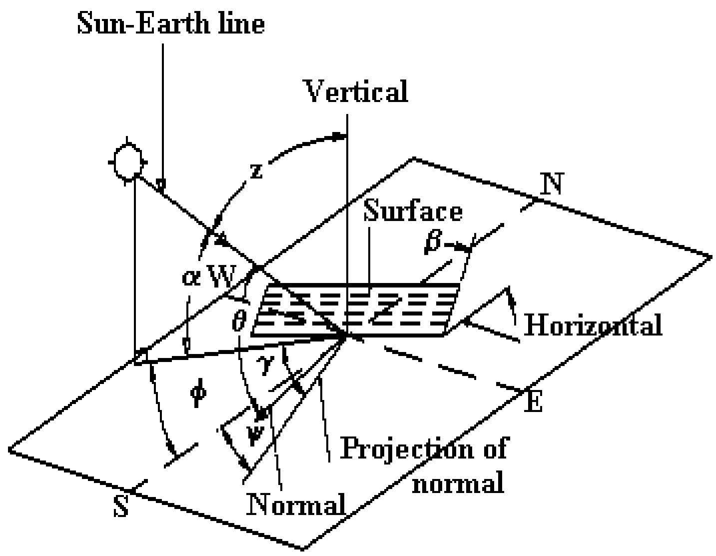
θ, the angle of incidence, is the angle between the solar rays and a line normal to the surface.

The position of the sun may be expressed as a function of solar altitude and the solar azimuth as shown in Figure 25 below. These angles are a function of the local latitude L and the solar declination δ, which is a function of the date and the apparent solar time (AST) expressed as the hour angle h:

> h = 0.25· (number of minutes from local solar noon) given in degrees. (h is positive in the afternoon.)

The declination angle is given by

$$\delta = 23.45\cdot deg\cdot sin\left(360\cdot\frac{284+n}{365}\cdot deg\right)$$



z	Zenith angle	θ	Incidence angle
α	Solar altitude	ϕ	Solar azimuth
β	Tilt angle	ψ	Surface azimuth angle
γ	Surface solar azimuth		

Figure 25, Definition of Solar Position

$$\alpha = \operatorname{asin}(\cos(L)\cdot\cos(\delta)\cdot\cos(h) + \sin(L)\cdot\sin(\delta))$$

$$\phi = \operatorname{acos}\left(\frac{\sin(\alpha)\cdot\sin(L) - \sin(\delta)}{\cos(\alpha)\cdot\cos(L)}\right)\cdot\frac{h}{|h|}$$

As can be seen from the diagram:

$$z = 90\cdot\deg - \alpha\cdot\deg$$

$\gamma = \phi - \psi$ (Note that ψ is negative and ϕ positive in the sketch)

$$\theta = \operatorname{acos}(\cos(\alpha)\cdot\cos(|\gamma|)\cdot\sin(\beta) + \sin(\alpha)\cdot\cos(\beta))$$

Angle of incidence (if γ is greater than 90 deg or less than 270 deg, then γ=0)

Example: Determine the local solar azimuth and altitude at 8:30 Central Time on October 23 at 32 deg North latitude and 95 deg West longitude. Also, determine the incidence angle for a vertical surface facing southeast:

$n := 273 + 23$ $LST := 8.5\cdot hr$

$LSM := 90\cdot\deg$ $LON := 95\cdot\deg$

$ET(n) = 14.497\,min$ $L := 32\cdot\deg$

$$AST := LST + ET(n) + 4\cdot\frac{min}{\deg}\cdot(LSM - LON)$$

$$AST = 8.408\,hr$$

Hour Angle:

$$h := (AST - 12\cdot hr)\cdot\left(15\cdot\frac{\deg}{hr}\right)$$

$$h = -53.876\,\deg$$

$$\delta := 23.45\cdot\deg\cdot\sin\left(360\cdot\frac{284 + n}{365}\cdot\deg\right)$$

$$\delta = -12.446\,\deg$$

$$\alpha := \operatorname{asin}\begin{pmatrix}\cos(L)\cdot\cos(\delta)\cdot\cos(h)\ ...\\ +\sin(L)\cdot\sin(\delta)\end{pmatrix}$$

$$\alpha = 21.963\,\text{deg}$$

$$\phi := \operatorname{acos}\left(\frac{\sin(\alpha)\cdot\sin(L)-\sin(\delta)}{\cos(\alpha)\cdot\cos(L)}\right)\cdot\frac{h}{|h|}$$

$$\phi = -58.264\,\text{deg}$$

Note that the solar azimuth is negative because it is east of south.

For a vertical surface facing southeast,

$\beta := 90\cdot\text{deg}$ $\quad\psi := -45\cdot\text{deg}$ . . . (East is negative)

$\gamma := \phi - \psi$ $\quad\gamma = -13.264\,\text{deg}$

$$\theta := \operatorname{acos}(\cos(\alpha)\cdot\cos(|\gamma|)\cdot\sin(\beta) + \sin(\alpha)\cdot\cos(\beta))$$

$$\theta = 25.487\,\text{deg}$$

8.5.2 *Angular dependence of glazing optical properties*

The angular dependence of a single sheet of coated or uncoated glass is extrapolated from its normal properties by the procedure described in ASHRAE fundamentals handbook 2001, SI edition, Chapter 30, “Determining the properties of uncoated glazing layers from normal incidence measurements”. This extrapolation uses angular data for CLEAR and BRONZE glass as found in ASHRAE 30.22, Table 12.

8.5.3 *Optical properties of the Double-Layer Glazing system*

For the determination of the optical properties of a double-glazing system, follow the procedure described in ASHRAE fundamentals handbook 2001, SI edition, chapter 30 “Optical properties of multi-layer glazing systems”.

8.6 Structural model

8.6.1 Introduction

This paragraph gives a description of the structural model for a 2 lite insulating glass unit that is implemented in 'SealSim 1.1. When the structural model is selected, for each time step:

- The lite deformation is determined
- The deformation of the inner, outer and wet seals is determined, where thermal deformation of the sash and spacer bar is taken into accounted. The seals behave visco-elastically (time-history effect).

Loads on the system (of lites and seals) taking into account the deformation calculations are:

- Pressure differences over the gas space,
- Wind loads (See ASCE 7 and ASHRAE Fundamentals 2001, chapter 16)
- Thermal expansion/contraction of the spacer bar
- Thermal expansion/contraction of the sash
- Thermal expansion/contraction materials
- Gravitation

The structural response of an IG unit is assumed to be the (coupled) response of the insulating gas, the two glass lites, the seals and (if present) the metal spacer, to external loads and material degradation. The external loading is due to barometric changes and wind loads, whereas considered material degradation includes degradation due to aging, chemical degradation and temperature changes. Hence, the structural response of the unit is dependent on the thermal behaviour and on the composition of the insulating gas. Therefore, the model for the structural response of the IG unit is coupled with the thermal model for the unit and with the model for the penetration of water vapor into the unit. These latter two models are described elsewhere and are not considered in this paragraph. However, the chain of calculations to solve for the coupled models for structural response, thermal response and water vapor penetration will be discussed. Furthermore, for a speed-up of the computations some mass balance calculations for the gas composition are considered in the model for the structural response as is explained in section 8.7.2.

In the next section the chain of model calculations for a time step is described, which is followed by a discussion of the way the response of the two glass lites is determined. The coupling of this response with a lumped mass balance equation for the filling gas is then explained. In the last section it is pointed out how the response of the seals (and the metal spacer) is determined using a set of springs and dashpots.

8.6.2 *Coupled model calculations*

The coupling of the structural model with the thermal model and the model for the penetration of water vapor in the overall program is reflected in the calculation sequence depicted in figure26.

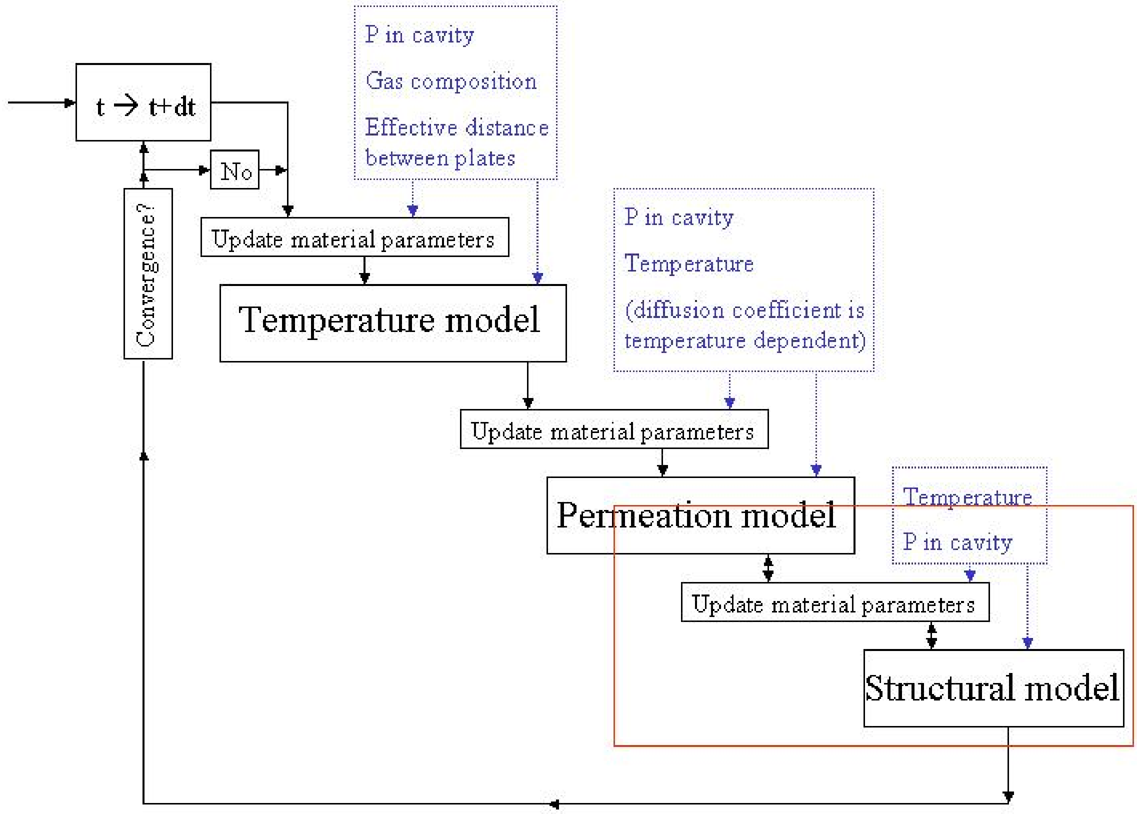


Figure 26, - SealSim 1.1 coupled model calculations

In figure 26 it is seen that after each time increment (with time step dt, box in the left-up corner), first the temperature model is solved, which is based on the most recently determined solutions for the permeation and structural models The second model considered is the one for water vapour permeation, in which the most recently determined temperature and structural data is used. The last model considered is the one for structural response, where again the most recently solutions for the temperature and the permeation models are used. This is reflected in the figure by the blue boxes and connection arrows with both the model boxes and the boxes that indicate the actions to update the relevant material parameters.

As one such sequence of calculations may still result in solutions for the three (coupled) models that do not reflect a good balance, the solution procedure for the structural model is followed by a (convergence) check for balance. If one has obtained balance, the calculation procedure for this time step is terminated and SealSim 1.1 proceeds with the next time step. When the balance is still not sufficient another sequence of model calculations is performed. This convergence check is based on the residuals for the model equations based on the most recently determined set of model solutions. These residuals have physical significance: For the temperature model this residual` indicates a balance in heat exchange and for the permeation model it concerns a (molecular) mass balance.

For the structural model two residuals for a convergence check are required, where one also equates to a check for mass balance. This is due to the fact that in the structural model there is already provision for a part of the coupling with the permeation model as is reflected in figure 25 by means of the red box that covers the structural model and part of the permeation model. In the next section the bending of the glass lites is described, which will enable us to elaborate on this coupling. The other convergence check for the structural model concerns a balance of forces per unit length as will be discussed in Section 8.7.

8.6.3 *Deformation of lites under loading*

For the deformation of the two glass lites of the IG unit, it is assumed that such lites have a small length in the direction perpendicular to the lites (i.e. the thickness) in comparison with the two (horizontal and vertical) dimensions along the plate. Furthermore, it is assumed that the loads are such that the lite deflections in the perpendicular direction are much larger than the ones in the planes of the lites. Hence, only deflections in the perpendicular direction are taken into account, where it is assumed that these deflections are relatively small such that the classical elastic plate theory as described in Theory of Plates and Shells, Timoshenko and Woinowsky-Krieger (1959) may be assumed.

It should be noted that alternative models are available for deformation calculations for the two glass lites (e.g. Reissner, Kirchhof and Von Karmann non-linear plate equation). However, the current modelling approach does allow for fast (and relatively accurate) calculations. This aspect is quite important as the deformation model has to be applied many times during simulation runs with SealSim 1.1.

Let us consider now one lite (plate) with:

a	Horizontal length (in [m]) of the lite
b	Vertical length (in [m]) of the lite
h	Half the thickness (in [m]) of the lite
x	Horizontal coordinate (in [m]) with 0 < x < a (in [m])
y	Vertical coordinate (in [m]) with -b/2 < y < b/2
E	Young's modulus (in [Pa])
ν	Poisson's ratio (in [-])
q	(Constant) load (in [Pa]) applied in thickness direction

If one assumes the lite (plate) is simply supported, chapter 30 of Timoshenko and Woinowsky-Krieger (1959) gives us the following solution for w (in [m]), the deviation in perpendicular direction,

$$w(x,y) = \frac{q}{24D}(x^4 - 2ax^3 + a^3x) + \frac{qa^4}{D}\sum_m^{\infty}\left(c_1\cosh\left(\frac{m\pi y}{a}\right) + c_2\left(\frac{m\pi y}{a}\right)\sinh\left(\frac{m\pi y}{a}\right)\right)\sin\left(\frac{m\pi x}{a}\right)$$

Where in the summation m is only taken to be odd and:

$$c_1 = -2\frac{a_m\tanh(a_m)+2}{\pi^5 m^5\cosh(a_m)}$$

$$c_2 = \frac{2}{\pi^5 m^5\cosh(a_m)}$$

And:

$$a_m = \frac{m\pi b}{2a}.$$

In order to determine the lite deflections accurately in the structural model the summation is limited to a finite number of terms in such a way that the remaining (infinite number of) terms that are left out are (relatively) small.

In a similar way derived data can be determined out of the expression for the deviation w, such as

M_{xx} Momentum per unit length (i.e. in [N])

M_{xy} Momentum per unit length (i.e. in [N])

M_{yy} Momentum per unit length (i.e. in [N])

Q_x Horizontal force per unit length (i.e. in [N/m])

Q_y Vertical force per unit length (i.e. in [N/m])

As can be found in the same chapter of the aforementioned book of Timoshenko and Woinowsky-Krieger,

Three mean (integrated) quantities are determined for both lites and used by the structural model:

$w_{vol} = \int_0^a \int_{-b/2}^{b/2} w(x,y)dxdy$ Volume (in [m*m*m] connected to lite deviation (i.e. w integrated over x and y),

$Q_x^{iy} = \frac{1}{b}\int_{-b/2}^{b/2} Q_x(0,y)dy$ Force per unit of length (in [N/m]) in the deflection direction on a vertical boundary,

$Q_y^{ix} = \frac{1}{a}\int_0^a Q_y(x,-\frac{b}{2})dx$ Force per unit of length (in [N/m]) in the deflection direction on a horizontal boundary.

These expressions are given by:

$$w_{vol} = \frac{q}{24D}\frac{ba^5}{5} + \frac{qa^4}{D}\sum_m^\infty (c_1 b_m \sinh(a_m) + c_2(b\cosh(a_m) - b_m \sinh(a_m)))b_m$$

$$Q_x^{iy} = -\frac{qa}{2} + \frac{2\pi^3 qa}{b}\sum_m^\infty m^3 c_2 b_m \sinh(a_m)$$

$$Q_y^{ix} = -2\pi^3 q \sum_m^\infty m^3 c_2 b_m \sinh(a_m)$$

Where in the summation m is only taken to be odd and

$$b_m = \frac{2a}{m\pi}.$$

In the structural model the expressions for w, w_{vol}, Q_x^{iy} and Q_y^{ix} are determined for both glass lites based on the (constant) load q. In these calculations there is already provision for a coupling with the model for water vapor permeation as is discussed in the next section. The (constant) load q for both lites is composed of the structural model based on the weight load (q_{weight}) the barometric pressure ($p_{barometric}$,) the wind load (q_{wind}) and the filling gas pressure (p_g), all in [Pa]. According to

$$q = p_{barometric} - p_g - q_{wind} + q_{weight}$$

In the calculation of the weight load there is a provision for consideration of the azimuth and tilt angle of the IG unit. Furthermore, the wind load is determined from

$$q_{wind} = 0.5 C_{wl} \rho_{air} v_{wind}^{\ 2}$$

Where ρ_{air} is the surrounding air density (in [kg/ (m*m*m)], v_{wind} is the wind speed (in [m/s]) and the value of the constant C_{wl} (in [-]) depends on whether the wind direction is leeward or windward.

8.6.4 *Coupling with lumped mass balance for gas*

The applied loads in the thickness direction on both glass lites of the IG unit are linearly dependent on the total filling gas pressure p_g^{n+1} for the new time step as pointed out in the previous section. This pressure though has to fulfil the lumped mass balance equation for the filling gas, i.e.

$$\frac{w_{vol,g}^{n+1} p_g^{n+1} M_g^{n+1}}{RT_g^{n+1}} - \frac{w_{vol,g}^{n} p_g^{n} M_g^{n}}{RT_g^{n}} = \Delta t * flux_g$$

Where the superscript n and $n+1$ indicate the old and new time level, respectively, and

M_g Total molecular weight (in [kg/mole]) of filling gas

R Gas constant (in [J/ {mole*K)]

T_g Temperature (in [K]) of filling gas

$flux_g$ Flux (in [kg/s]) of filling gas out of cavity

$w_{vol,g}$ cavity volume (and filling gas volume) (in [m*m*m], which can be easily determined from a difference of the volumes connected to the deflections of the two lites (see previous section) and the addition of a volume that corresponds to the distance between the two lites.

With the loads of the two glass lites linearly dependent on the filling gas pressure, it is seen from the previous section that (assuming the distance between the boundaries of the two plates to be constant per time step), among others, $w_{vol,g}$ is also linearly dependent on the filling gas pressure and hence the lumped mass balance equation reduces to a quadratic expression for p_g^{n+1}.

Therefore, the structural model can easily account for a coupling with the permeation model by calculating the coefficients of this quadratic expression in order to solve for p_g^{n+1}. With this new filling gas pressure then the values for deflection w and (mean) forces per unit length Q_x^{iy} and Q_y^{ix} can be determined. This data serves then as input for a set of spring-dashpot systems that models a typical cross section of the unit with the several seals (and metal spacer). From this set of spring-dashpot systems the typical structural response of the seals (and metal spacer) is calculated. Hence, for example, stresses and deformations in the seals and the new distance between the glass lite boundaries are obtained from this model. These parameters are then used in a next iteration of the chain of model calculations for a time step as described before. The description of this set of spring-dashpot systems is found in Section 8.6.6.2.

The typical cross section considered with the set of spring-dashpot systems cannot be really connected to a specific position in the IG unit. It should be seen as a model for the mean/maximum structural response of the seal system as only the maximum of the (mean) forces per unit length Q_x^{iy} and Q_y^{ix} serves as main input to the deformation calculations by means of the spring-dashpot systems.

The coupling between the structural model and the permeation model discussed in this section is schematically given in figure 27. In the figure it is seen that first there is a provision for an equilibrium between the deflections of the glass lites, resulting from filling gas pressure after which the structural response of the seals (and metal spacer) are brought in equilibrium with the lite deformations.

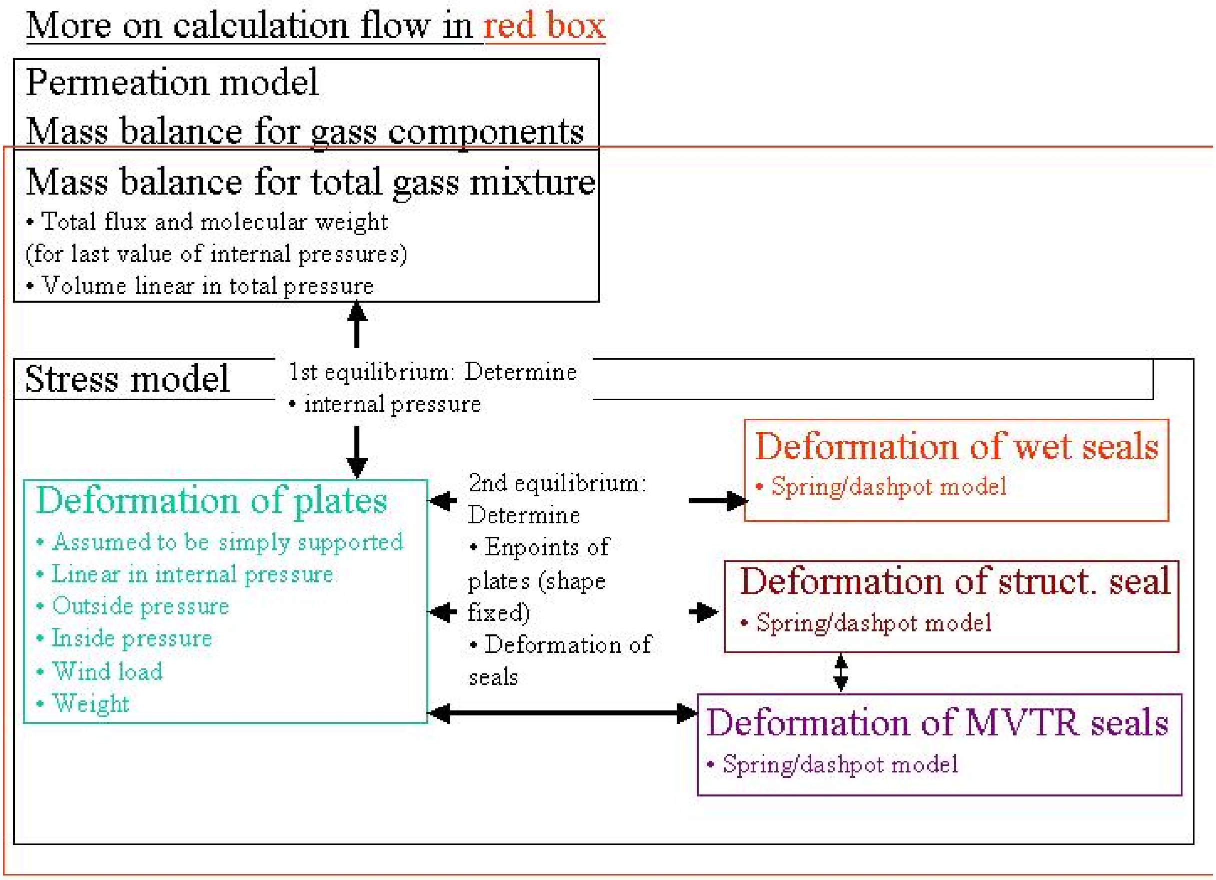


Figure 27 - Structural model calculations

Note that one of the convergence checks for the structural model is based on the residuals of the above equation of this section; i.e. a mass balance.

In the next section a general explanation is given of the space behaviour of the seal materials.

8.6.5 *Viscoelastic behaviour of polymers, general*

General
Amorphous polymers can show a range of mechanical properties from viscous fluids to elastic solids depending on time scale, ambient temperature and diluent concentration, as can be seen in figure 28.

The polymer changes from a "glassy phase", characterised by a high modulus, to a "rubbery phase" with significantly lower modulus, as time advances, temperature and moisture content increase. In between is a transition "leathery phase", the transition is defined by the glass transition temperature. The magnitude of the glass transition temperature has been attributed to the free volume of the polymer, defined as the difference between occupied and specific volume of the polymer. The free volume increases with the diluent concentration (moisture content). An expression for the glass transition temperature proposed by Kwei providing for secondary interactions is:

$$T_g = \frac{T_{g1}W_1 + kT_{g2}W_2}{W_1 + kW_2} + qW_1W_2 .$$

Where T_g (in [K]) is the glass transition temperature of the polymer diluent mixture, W is a weight fraction, k is an adjustable parameter for free volume effects, q is an adjustable parameter for secondary interactions, 1, 2 denote polymer and diluent, and T_{g1} and T_{g2} denote reference temperatures.

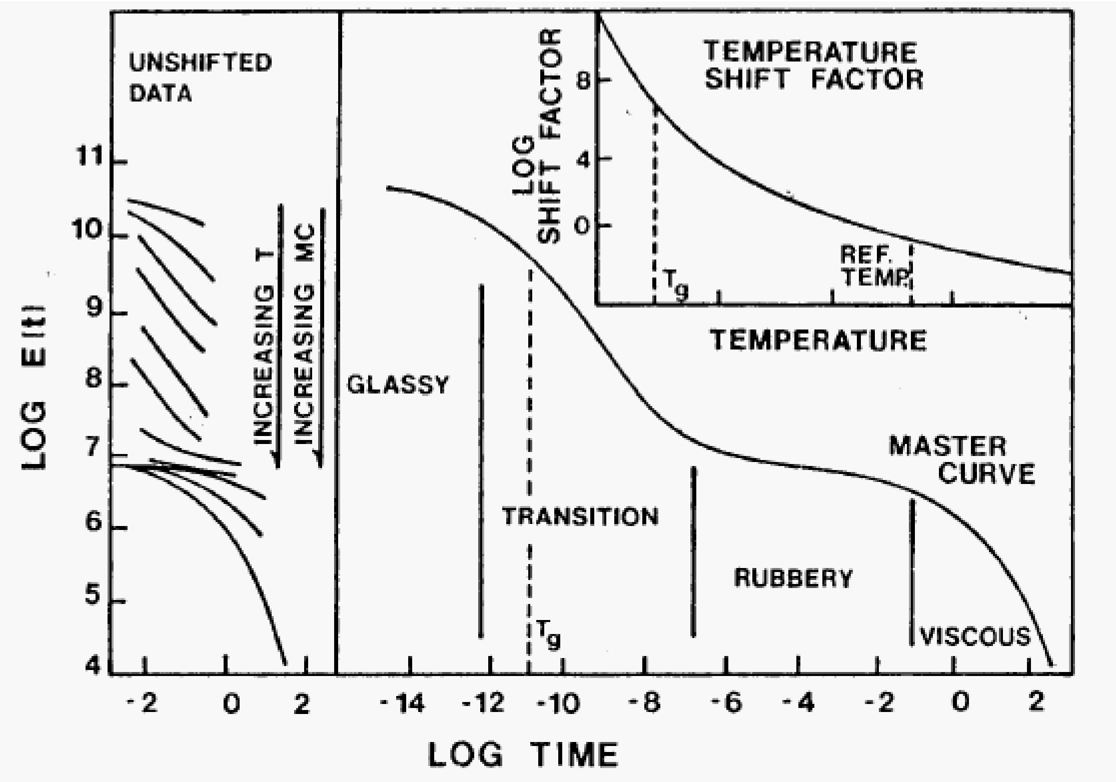


Figure 28 - Typical change of relaxation modulus E (t) of an amorphous polymer with time and temperature.

In this phase of the project we assume that the rubber is above the glass transition temperature, where the glass transition temperature is constant. The viscoelastic properties can be represented by the creep compliance D (t) (ε=σD (T)), or relaxation modulus (σ=εE (T)).

Time-temperature equivalence of viscoelastic properties
In general a time-temperature equivalence of the viscoelastic properties is observed [Williams-Ferry]. The basis of this principle is that temperature accelerates the time dependent response of the material. Accelerated testing methods are based on this equivalence principle. The time dependent material properties are determined at different temperature levels and shifted horizontally along the time log axis through a time multiplier (shift factor), until a smooth curve is obtained. This is the so-called "master curve". The "master" curve describes the time dependence of the investigated property at a reference temperature. The property at other temperatures is calculated from the "master" curve with the reduced time principle, or shift factor. The observation of the time-temperature superposition was in the first instance empirical. Later a theoretical basis was developed where the temperature shift factors can be calculated on the free volume concept. When the glass transition temperature of the polymer is chosen as the reference temperature, the temperature shift factor can be determined above T_g by the Williams-Landell Ferry (WLF) equation (below Tg an Arrhenius type equation is appropriate).

$$\log(a(t)) = \frac{-C_1(T-T_g)}{C_2+T-T_g}$$

Where the constants C_1 (in [-]) and C_2 (in [K]) of the WLF equation, after being determined experimentally for several polymers, were defined as "universal" constants for cases where experimental validation is not feasible (C_1=17.44, C_2=52.1).

Mathematical representation of viscoelastic behaviour
According to linear viscoelastic theory, the time dependent response of a viscoelastic material, for an arbitrary loading history, can be expressed either in an integral or differential form, if a single creep (or relaxation) curve is available for a prolonged time period (e.g. experimentally collected). The (convolution) integral representation is based on the superposition principle, where the effect of a complex loading history can be equated to the sum of independent contributions of smaller load steps, the so called Boltzmann Superposition Integral. For creep this reads (similar for stress relaxation) as

$$\varepsilon(t) = D(t)\sigma(0) + \int_0^t D(t-\varepsilon)\frac{d\sigma}{d\varepsilon}(\varepsilon)d\varepsilon$$

The differential form is based on mechanical analogies, such as combined spring and dashpot systems. Creep behaviour in its simplest form is described by a spring and dashpot in parallel, a Kelvin element,

$$\frac{d\varepsilon}{dt} = \frac{D_0}{\tau}\sigma - \frac{1}{\tau_0}\varepsilon$$

Where $\tau_0=\eta/E$ retardation or relaxation time, D_0 the compliance of the spring, E the modulus of the spring, η the viscosity of the dashpot, D the compliance of the spring, '0' denotes a specific reference temperature. The time dependent response of a Kelvin element for a step load reads as

$$\varepsilon(t) = \sigma(0)D(t)$$

Where

$$D(t) = D_0(1-e^{-t/\tau_0})$$

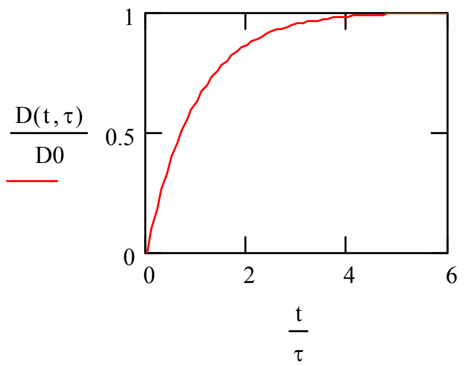


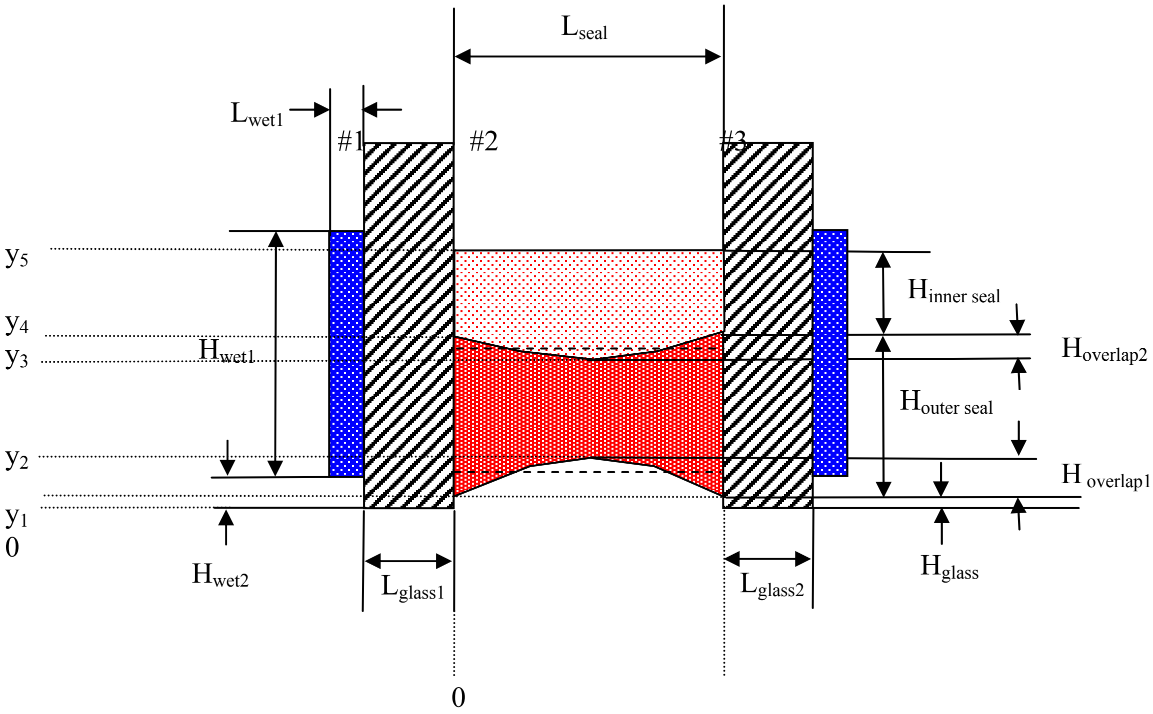
Figure 29, - Time dependent response of a Kelvin element for a step load

Relaxation behaviour is described by a Maxwell element, a spring and dashpot in series. Description of more complex material behaviour can be obtained by combinations of Kelvin and Maxwell elements. In the next section the system of springs and dashpots is described that is was used to model the material behaviour and deformations of the seals and metal spacer of the IG unit.

8.6.6 *Spring-dashpot system for seals and metal spacer*

8.6.6.1 *Geometry*

The configuration of the sash-seals-spacer-lites system is depicted below for two classes of IG units: TPS systems (without spacer) and Box-Spacer systems.



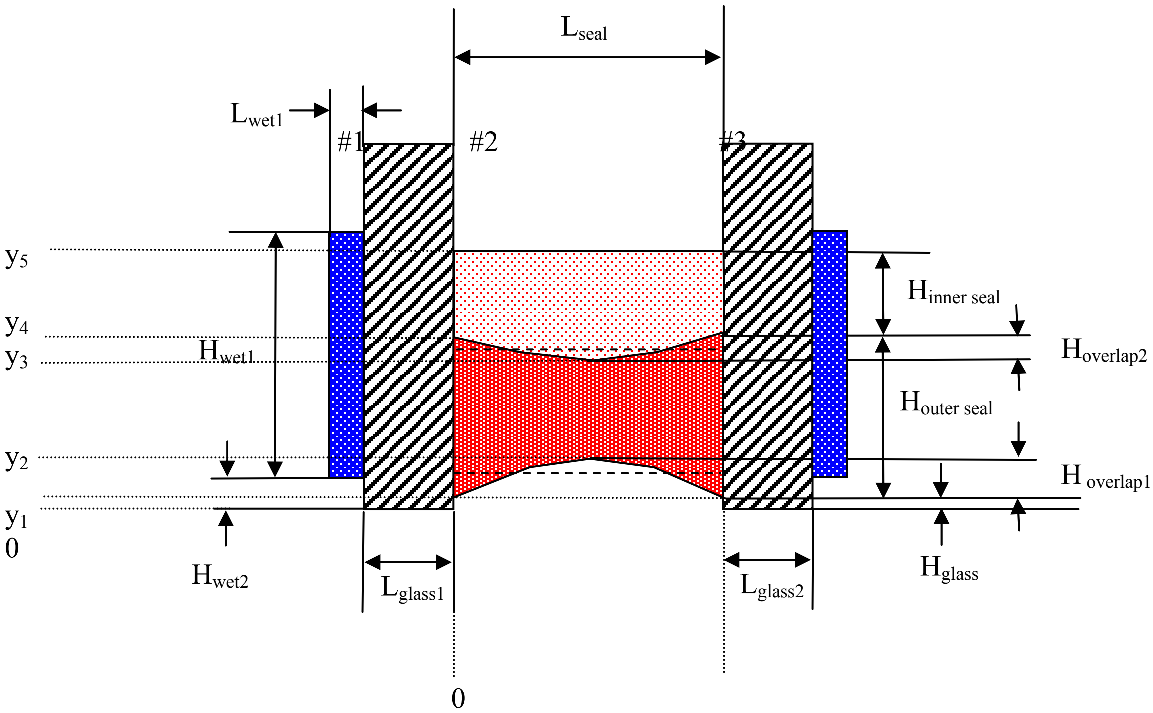


Figure 30 - TPS system

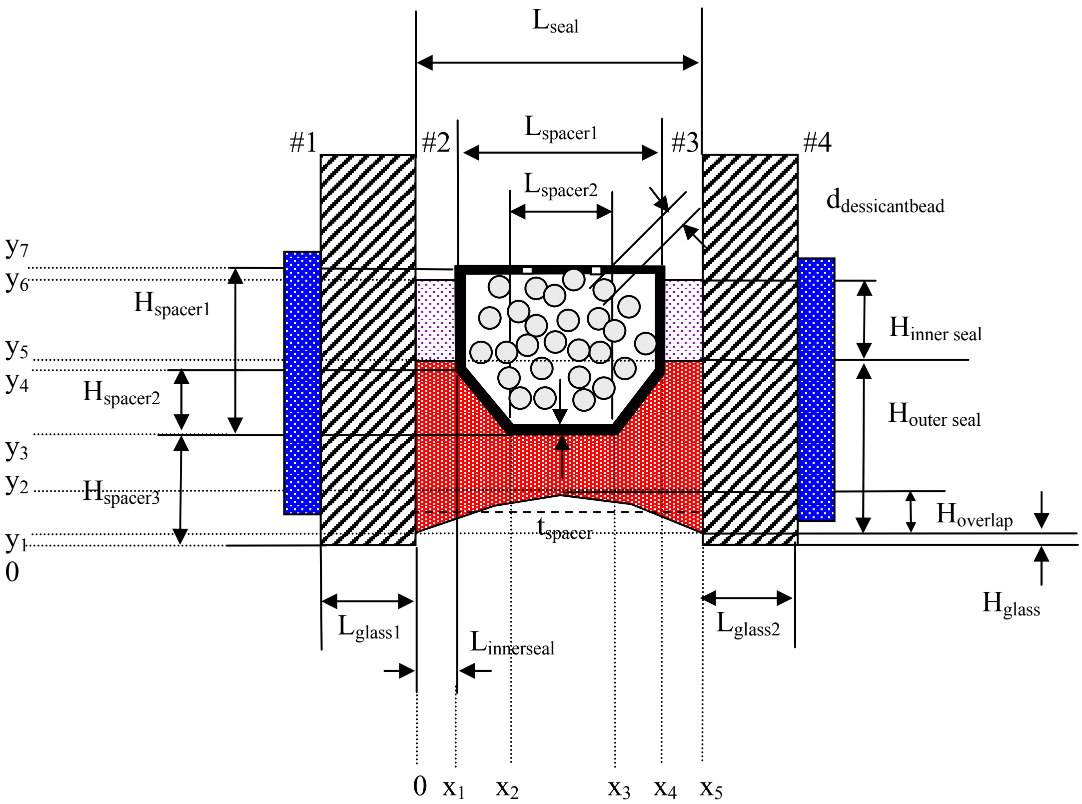


Figure 31 - Box-Spacer system

8.6.6.2 *Model description*

To describe the mechanical behaviour of the TPS-system and Box-Spacer system the components are represented by mechanical elements built up from springs (representing elastic behaviour) and dashpots (representing viscous—or damping—behaviour). The metal spacer in the box-spacer system is treated as a purely elastic component, whereas the seals are, in principle, viscoelastic components. Each viscoelastic component is modelled by a single-mode Kelvin-Voigt element, which is suited for describing the effects of creep, i.e., the time-dependent change in strain due to the application of a stress (caused by the load forces exerted by the glass window lites on the system). This is all reflected in the two figures below for both normal and shear loading for the Box-Spacer system. As the stiffness of the glass window lites are considered infinitely large compared to the stiffness of the other elements, the lites are not represented by mechanical elements.

Concerning the loading of the system, a distinction is made between normal loading (i.e., normal to the glass window lites) and shear loading (i.e., in the direction parallel to the glass window lites).

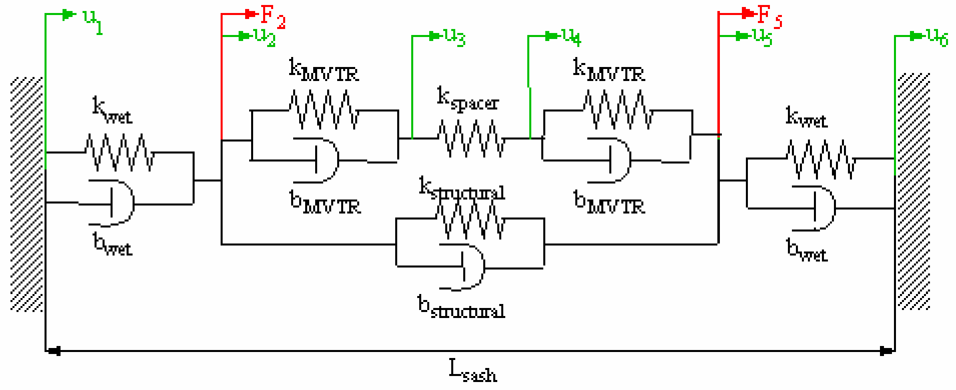


Figure 32 - Spring-dashpot system for normal loading of Box-Spacer system

Normal loading originates from three sources:

- Normal loads exerted by the glass window lites on the system which are due to the lite deflections in the lite thickness direction, i.e. the maximum of Q_x^{iy} and Q_y^{ix}
- Thermal expansion of the sash in the normal direction
- Thermal expansions of the seals and spacer in the normal direction

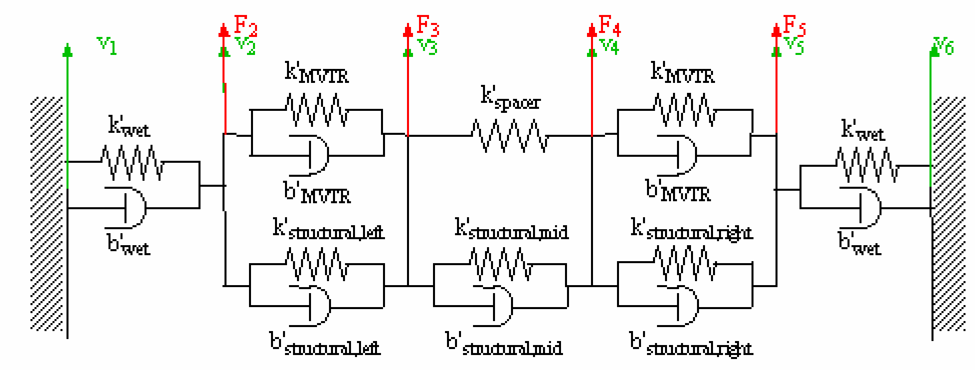


Figure 33 - Spring-dashpot system for shear loading of Box-Spacer system

Shear loading can be attributed to three sources as well:

- Shearing loads exerted by the glass window lites on the system due to the weight of the lites
- Shearing load exerted by the difference between filling gas pressure and ambient pressure
- Differences in thermal expansion in shear direction of glass window lites, sash, and spacer.

Because of the shearing load caused by the spacer, the structural seal in a Box-Spacer system is split into three parts, of which the two outer parts have a 'length' (measured perpendicular to the glass window lite) that is equal to the length of the MVTR seal.

All spring and dashpot constants are calculated from Young's moduli, Poisson's ratios and dynamic viscosities of the seal materials as well from the seal dimensions. Note that the spring and dashpot constants *k* (and *b*) for normal loading differ form the constants *k'* (and *b'*) for shear loading, as the first one is determined from Young's modulus and the second one from the shear modulus (in [Pa])

$$G = \frac{E}{2(1+\nu)}$$

Whereas most material parameters can be prescribed by the user as linear functions of time and temperature, the temperature dependence of relaxation times for the seals (defined as the ratio of dynamic viscosity and Young's modulus) is described by the established WLF-equation, which is generally valid for the temperature range from Tg (the glass transition temperature) up to Tg+100°C.

The systems that are ultimately calculated for each time step and for each loading type can be represented as

$$B\dot{u} + Ku = f,$$

In which u is the vector of displacements, B and K are the damping and stiffness matrix, and f is the load vector.

8.6.6.3 *Influence of bending of glass window lites on seals*

Due to the external loads, the glass lites may be subject to bending (either inward or outward), thereby causing a difference in the extensions of the innermost and outermost seals between the two lites. It is assumed here that the bending of the lites is a result of the external loads only, and is not caused by the difference in stiffness between the innermost and outermost seal. The bending of a lite is given by its angle φ_{pane} with respect to the axis along the un-deformed lite length

$$\varphi_{pane} = \arctan(w'_{pane}),$$

Where w'_{pane} is the derivative of the glass lite deflection w_{pane} that can be easily determined from the expression for the deflection given in one of the previous paragraphs.

The bending of the lites can be taken into account by a modification of the force balance in the set of springs and dashpots as is explained for the TPS system is and shown in figure 29.

The bending of the lite causes extra displacements $u_{MVTR,\ extra}$ and $u_{struc,\ extra}$ at nodes 2 and 3 in the set of spring dashpots given by

$$u_{MVTR,extra} = a_{MVTR}\sin(\varphi_{pane})$$

$$u_{struc,extra} = a_{struc}\sin(\varphi_{pane})$$

Where a_{MVTR} and a_{struc} are the offset distances of the point of action of the forces on the seals relative to the point of action of the force on the wet seal; note that a_{struc} has a negative value, as it is applied in the downward direction.
The net result of the bending of the lite on the reaction forces should be zero. To accomplish this, the displacement u_2 and u_3 (and their time derivatives) in the original system of equations should be replaced by 'new' displacements u^*_2 and u^*_3 that are given by

$u_i^* = u_i + a_i \sin(\varphi_{pane})$

$\dot{u}_i^* = \dot{u}_i + a_i \cos(\varphi_{pane})\dot{\varphi}_{pane}$,

With i = [struc, MVTR, wet], $a_{wet} = 0$ and φ_{pane} the bending angle of the lite at node 2 or 3. This means that the system of equations has to be modified to

$B\dot{u} + Ku = f - Ba^T \dot{u}' - Ka^T u'$,

Where 'a' is an array with point of action offsets

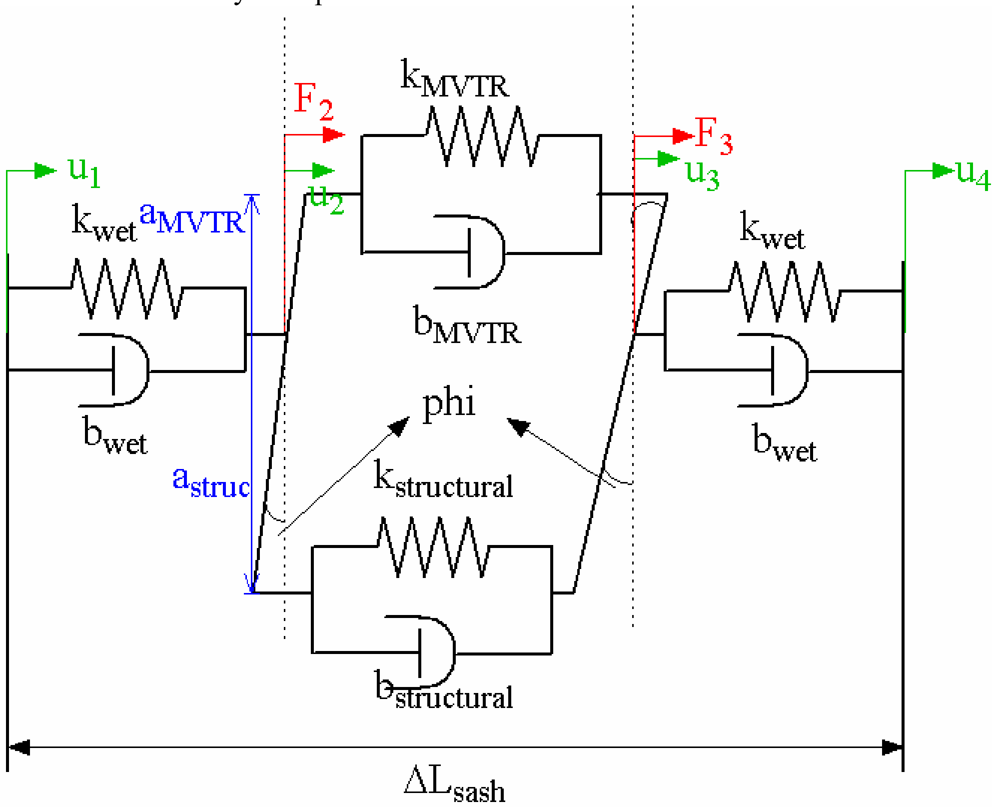


Figure 39, - Bending in set of spring-dashpot systems for TPS system

8.6.6.4 *Input and output data*

Apart form the material data and component dimensions that have been defined through the input file, the following data serves as the main input for the spring-dashpot calculations

- The type of IG unit (TPS or box-spacer)
- The time at the current time step, at the previous time step and at the start
- Mean values for the loads in normal and shear directions exerted by the glass window lites on the seal systems, including the load due to the weight of the glass lites.
- The temperatures of the system components at current and previous time step.
- The calculated displacements at the previous time step and previous iteration.
- The derivatives of the glass lite displacements (representing the bending of the lites).

Among the results that are determined are:

- The effective (Hubert-Hencky) stresses in the seal components (in [Pa])
- The displacements (in [m]) in the set of spring-dashpot systems, from which e.g. the distance between the lites can be updated
- The strains and shears of the system components (dimensionless)
- The residuals of the solved systems (in [N/m])

This effective stresses in the seal components given by

$$\sigma_{eff} = \sqrt{\sigma^2 + 3\tau^2}$$

(Determined from the normal stress σ and shear stress τ for the component)

Residuals indicate convergence of the solution within an iteration loop and are calculated as

$$f_{current} - B_{current}\left(\frac{u - u_{old}}{\Delta t}\right) - K\left(u - u_{old}\right).$$

With u the most recent solution obtained for the current time step. This residual has the dimension of load per unit length as all (external) forces in the system are per unit length.

8.6.7 *Chain of structural model calculations*

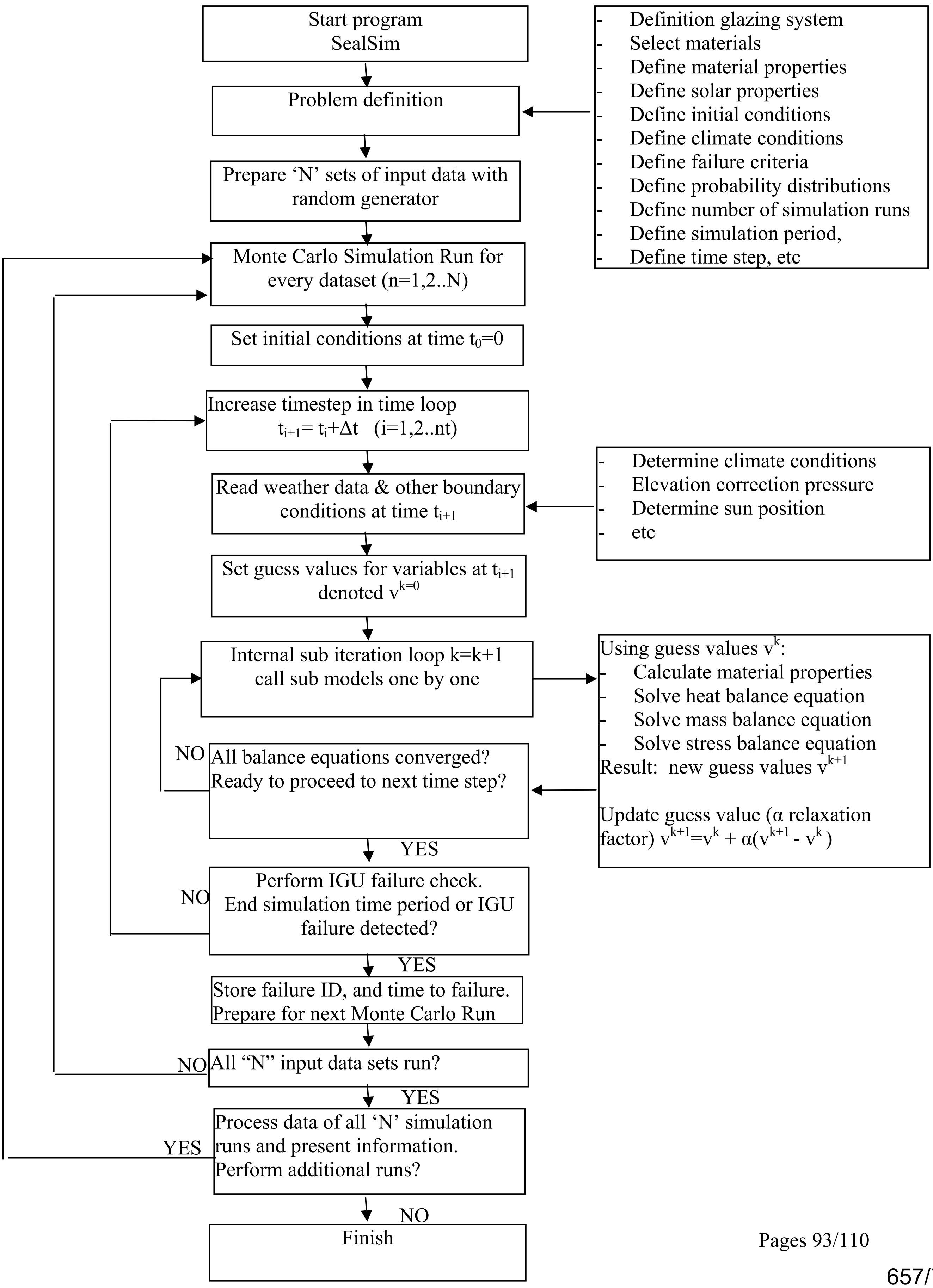
For a specific time-step and sub-iteration the following chain of structural model calculations is performed:

1. Based on a load and updated material parameters for the glass lites, their deflection and derived data is determined
2. With some of this data, and the actual loads for the lites, the coefficients for the quadratic equation for the new gas filling pressure are determined
3. From these coefficients the pressure is calculated, from which the total loads for the lites can be determined such that the actual deflection and its derived data are determined
4. Subsequently the external normal and shear loads for the system of seals can be found
5. Based on actual time, actual temperature, etc. all viscoelastic (spring-dashpot) constants are updated
6. Based on the new temperatures the thermal expansion of the components is determined and transferred to equivalent loads
7. Seal deformations (i.e., displacements) for the normal loading situation are determined and the residuals (for the previous displacements found) are updated
8. Seal deformations (i.e., displacements) for the shear loading situation are determined and the residuals (for the previous displacements found) are updated
9. From the seal deformations found, seal strains and stresses are calculated.

8.7 Coupled Physical Models, Iterative procedure

As the sub models are coupled, i.e., a change in gap width results in a change in temperatures, gas in the gas space contracts/expands, resulting in change in pressure difference over the lites, affecting the gap width etc, an iterative procedure is used to solve the various equations of the sub models. Within a time step, the sub models are called one by one repeatedly, and when new information becomes available about temperatures, pressures, deflections, material properties, etc, the old values are immediately replaced by the latest values obtained, until the values do not change significantly anymore per sub iteration. In that case the sub models are considered to be converged, after which SealSim 1.1 will proceed to the next time step in the simulation.

9 Appendix #1 Calculation procedure SealSim 1.1, flowchart



Calculation procedure 'SealSim 1.1'

(1) Problem Definition

Define glazing system
- Define dimensions of glass and seal
- Window orientation (tilt, azimuth)
- Characteristics building/terrain (to calculate wind force)
- Define permeation short cuts due to corner keys etc.

Select materials
- Select material glass lites numbers 1 and 2
- Select polymer material outer seal
- Select polymer material inner seal
- Select desiccant present in outer seal
- Select desiccant present in spacer
- Define which fill gases are present and are involved in permeation
- Select frame (sash) material

Define material properties
- Define solid material properties
- Define polymer material properties
- Define desiccant material properties
- Define fill gases and gases involved in permeation
- Material properties are defined in the databases; at this stage they are not accessible by the user.

Define solar properties
- Read solar properties individual glass lite numbers 1 and no. 2 at normal incidence
- Emissivities of glass lites (long wave)
- Extrapolation of solar properties to any angle of incidence
- Properties defined in glazing-database (not editable by the user).

Define initial conditions (filling conditions)
- Temperature (uniform)
- Total pressure gas space
- Barometric pressure outside and inside (no wind load assumed)
- Volume fraction (mole fraction) or partial pressure of gases
- Amount of desiccant present
- Initial concentration of adsorbent in the desiccant
- Initial concentration of adsorbent in the polymer
- Initial seal length at filling, stress free

Define climate conditions
- Select weather station and climate period. The weather data in TMY2 also contain station location and elevation. Note: IGU elevation = station elevation or unless explicitly defined in extended TMY2 format
- Terrain characteristics at the weather station, anemometer height
- Note that during transport from production location to final location, the climate conditions (including barometric pressure etc) in general will change. It is assumed that this is accounted for in the weather file. This means that if existing weather data of a station are used, weather data during transport has to be inserted in this data file.
- Climate next to seal = weather climate, or, = explicitly defined as a function of time in a separate data file

Define simulation time
- Start simulation in time
- End of simulation in time
- Define (numerical) time step

Define failure criteria
- Define threshold levels at which IGU fails, e.g. the IGU fails when internal condensation occurs.
- Cohesive failure properties come from the database (can have a probability distribution)

Define numerical settings
- Iterative loop through individual balance equations
- Define convergence criteria & relaxation factors.

Define probability distribution and number of Monte-Carlo runs "N"
- The material parameters, failure criteria can have (1) "fixed" values (2) or posses a probability distribution (in case of a normal distribution: mean value and standard deviation). It is up to the user to decide this.
- A simulation run, however, takes only fixed values as input. Before simulation start therefore, a random number generator determines a fixed set of values, and then runs a simulation. By repeating this procedure several times, the results of these simulations runs can be statistically evaluated. The user specifies the total number of simulation runs, and it is up to the user to judge if this gives a statistically relevant output (only for a linear model can it be decided how many runs are required beforehand to give expected output accuracy, see documentation elsewhere).

(2) Prepare 'N' sets of input data with random generator

(3) Perform Monte Carlo Simulation Run for each set of input data (n=1, 2...N)

(3.1) Set initial conditions IGU (filling conditions)
- Specify initial conditions of IGU at time zero t_0=0
- For a given barometric pressure, initial gas composition and gas space pressure & temperature, calculate initial glass lite deflection and seal deflection (hence effective volume of the gas space)

(3.2) Time loop
- Determine current time $t_{i+1} = t_i + \Delta t$ (i=1,2..nt)
- Read weather data TMY2 at current time step, calculate angle of incidence of the sun on the window, correct pressure for window elevation differing from station elevation, correct wind speed for meteorological conditions and building conditions (terrain etc)
- Determine environmental conditions near seal, equal to environmental weather conditions or read from file
- Set values of variables at last time step as estimation values for variables at current time step
- Note about variables: We discern two types of variables, primary variables and secondary variables. Primary variables are temperature (heat balance equation), gas pressure and composition (mass balance equation components extended with Equation Of State EOS, in this case the 'ideal gas' law), and stresses and strains (deflections). Secondary variables are variables that are direct functions of the primary variables, for example gas conductivity is a (known) function of pressure, temperature and gas composition, the characteristic heat transfer coefficient is a function of length scale, temperature, pressure, etc. During the numerical resolution process a relaxation factor can be introduced for primary and secondary variables. A relaxation factor for primary variables is preferred.

  Iteration loop
  Internal iterations loop through individual balance equations to update estimated values:
  - Solve heat balance equation

    - Calculate new estimated temperatures in IG (using old estimates for temperature, average gas gap width between glass lites for heat transfer, material properties, etc), essential centre of glass calculation 1D
    - Calculate seal temperature or read data from file (time data)
- Solve mass balance equation for gas components, subdivided in three parts
    - Permeation inner & outer seal
        - Calculate amount and composition of gas entering/leaving the gas space through inner & outer seal (using old estimates for volume gas space, gas composition, gas pressures etc)
        - Last item is area-weighted summation of two one dimensional path (1) inner & outer seal present (2) inner seal missing.
        - Calculate how much gas is absorbed in desiccant (using old estimates for composition and pressure gas space)
    - Mass balance in the gas space
        - Calculate new value for gas space pressure and gas composition.
- Stress model, solve force balance
    - Calculate new stresses and deflections glass lite and seal, based on
        - Deformation history
        - Boundary conditions: prescribed sash displacement, thermal expansion on the spacer bar
        - Most recent estimates for gas space pressure, temperature, etc
- Update estimate for variables using under-relaxation.
- Update material properties (according to new estimate temperatures, etc)
- Loop through individual balance equations and update variable values until convergence of all balance equations is obtained (within preset error limit). If divergence is detected, restart iteration loop with more conservative relaxation factors.

- Go to next time step and repeat procedure until IGU failure criteria is encountered or user indicated simulation time period is exceeded
- Store data

(3.3) End time loop

- Stop simulation if simulation time period is exceeded or an IGU failure criterion is encountered.
- At interrupt, store data about current simulation run 'n'.
- Present statistical information for run 1 to 'n: how runs met criteria, how many runs were encountered for which a failure criterion occurred and the average lifetime, with standard deviation, of each failure criterion.
- Start another durability simulation until 'N' sets of input data are simulated (or break simulation on user interrupt).

Example, simulation time 10 years, 16 runs, results:
Run 1: no failure, hence life time of 10 years or more
Run 2: failure after 5 years, due to failure criterion no 2
Run 3: failure after 4 years, due to failure criterion no 1
Run 4: failure after 6 years, due to failure criterion no 2
Run 5: failure after 7 years, due to failure criterion no 2
Run 6-16: no failure, hence life time of 10 years or more

Statistical interpretation

- *The average life time is (12x10yr+5yr+4yr+6yr+7yr)/16 = 8.875 years or more*
- *75% of IGU's do have a life expectancy of 10 years or more*
- *25% of the IGU's fail within 10 years*
- *The IGU's that fail, fail after on average 5.5 years (sigma=1.29)*

Of IGU's that fail:
- *75% fail due to criterion no 2, on average after 6 years (standard deviation=1)*
- *25% fail due to criterion no 1, on average after 4 years (standard deviation=0)*

(4) End simulation

(4.1) Process data
- Process the data of all simulation runs (# passed, # failures + mean/standard deviation lifetime)
- Present information
- Depending on outcome, decide not to end simulation, but do perform additional Monte-Carlo runs, go to step (2) again.

(4.2) End simulation
- End simulation, if it is decided not to perform additional Monte-Carlo runs.

10 Appendix #2) Programmers details

General

The SealSim 1.1 program consists of two separate parts:

- The Graphical User Interface, referred to as the "**GUI**", and
- The calculation engine, referred to as the "**Engine**".

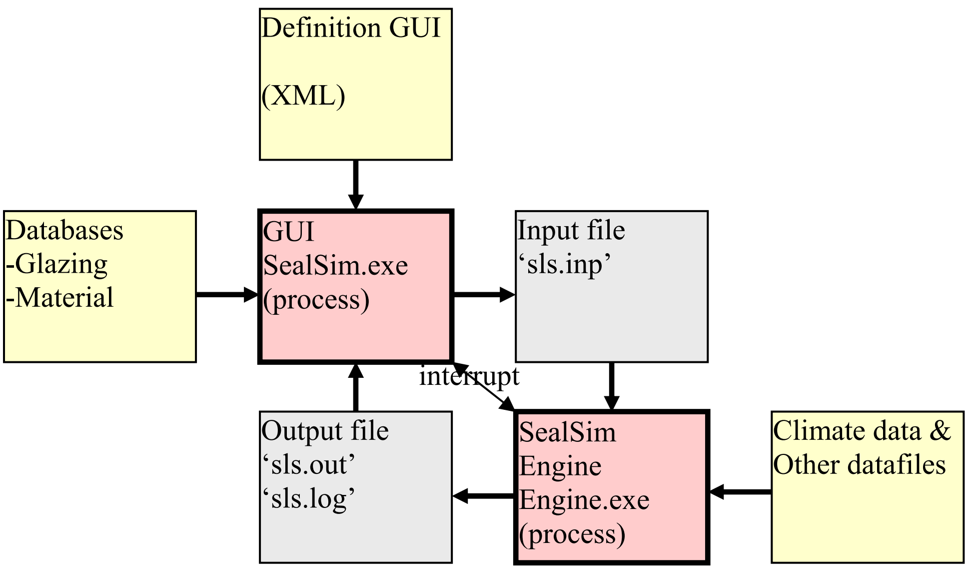
An advantage of a separate GUI and Engine is that it makes independent co-development of the GUI & Engine easier. This requires however a strict definition of the interface between the GUI and the Engine, that is in a format in which the different interface files are written, and the way in which communication occurs between the GUI and Engine (interrupt handling).

The **GUI** prepares a problem definition file "sls.inp", which is read by the Engine. As the name already indicates, the problem definition file contains all the necessary data required for a simulation to run, whether these are dimensions of the IGU, values of material properties, or references to files where data can be found (e.g. climate data files), etc. For the selection of solar/optical and material properties, the GUI references the International Glazing Database (IGDB) and the SealSim 1.1 database (SealSim.mdb). Also the GUI reads output files from the Engine for graphical representation.

The look of the GUI, as experienced by the user, i.e. its tree-like structure, is largely defined by an Extensible Markup Language XML file ("IGUxmlDataTree.xml"), which resides in the same directory as the GUI. Thus a user or programmer can change the wording of variables in the GUI, regroup variables in the tree structure, change minimum and maximum values of variables and change the units in the GUI and pop-up comments, etc. by changing the appropriate section in the XML file. In this way also can be specified which column in a database is to be referenced. The XML file format is self explanatory.

The **Engine** simulates the behaviour of the IGU in time, and writes a selection of the results to output files. These (ASCII) output files are read by the GUI for graphical presentation or can be read with a text-processor, e.g. WordPad.

For the GUI to signal that the Engine should start calculating, or for the Engine to signal that it finished the simulation, etc, there is an interrupt handling procedure between the GUI and Engine, described in a later paragraph.



GUI = Graphical User Interface

XML=Extensible Markup Language

IGDB=Internationa l Glazing Database

Engine=Calculation part of SealSim 1.1

Figure 35, Organisation of the SealSim 1.1 program

Program details

Separate GUI & Engine
- Independent co-development of GUI & Engine is easier
- Requires FORMAT definition of interface files: 'sls.inp', output 'sls.out', log: 'sls.log'
- Facilitates Interrupt handling via 'files' that are written in the directory where the SealSim 1.1 Engine resides.

GUI
- Language: C#
- Compiler: MicroSoft Visual C# …
- .NET framework (Version 1.1)
- Generic setup GUI: definition GUI by XML file
- Dynamic construction of the GUI-elements using easily editable XML files (no recompilation of GUI).
- XML file defines variable tree, access database, help, min, max, etc.
- Thus variables can be added, etc. without compilation of the GUI
- More flexible in the long-term
- Connection to Glazing database
- Connection to SealSim 1.1 database with properties of all materials

Engine
- Language: FORTRAN 90
- Compiler: Compaq Visual Fortran version 6.6B
- Embedded documentation (example)
  - Header description
  - Comments in routine
  - Debug variable
  - Enter/exit routine is written to log file
  - Error handling

SealSim 1.1 Database: "SealSim.mdb"
- Microsoft Access 2000

International Glazing Database (IGDB): "GlazingTPD.mdb"
- Microsoft Access 2000
- The user cannot write/change or delete items in the international Glazing Database. The GUI accesses the database by using a structured query.
- The SealSim 1.1 Glazing Database "GlazingTPD.mdb" is the same as the International Glazing Database "Glazing.mdb" as used in Optics5 (Version 13.4, date: 9-9-2003). It is identical, but for the fact that an extra query (qry TNO-TPDGlazingProp) was added by LBNL especially for SealSim 1.1. Information about the database can be found on http://windows.lbl.gov/materials/IGDB/

Engine subroutine documentation Example

```
!*******************************************************
!   SUBROUTINE read_tmy2 (filename, array, nnx, nny, nx, ny)
!
!   Description: Read climate DATA in tmy2 format (typical meteorological
!     year) and put them in array for storage and interpolation purposes
!
!   Extensions to tmy2 format for our purpose
!-----------------------------------------
!   Character positions (143:146) are claimed for extra information about
!     elevation in case the IGU-module is manufactured at another location
!     as the final location of usage of the IGU. This allows to enter
!     information about climate and elevation conditions in the meantime,
!     IF available.
!     If CHARACTER position (143:246) are blank it is assumed that the IGU
!     elevation is given by the city elevation
!   The manufactering elevation may also be given separate via the GUI.
!   If the elevation is specified via the tmy2 climate file,
!     this elevation information prevails over the elevation in the GUI
!
!   If a negative number is found on CHARACTER positions (2:3) it is
!     assumed that CHARACTER position (4:9) give the number of hours passed
!     Since 1 January 0:00 hour starting at user-defined year.
!
!     Created:    J.F.M. Velthuis, TNO-TPD-Delft
!     Date:       14 Aug 2003
!
!=======================================================
      SUBROUTINE read_tm2 (filename, array, nnx, nny, nx, ny)
!-------------------------------------------------------
!     Definitions
!-------------------------------------------------------
      CHARACTER (LEN=100), INTENT (IN):: filename
      INTEGER, INTENT(IN)           :: nnx, nny          ! maximum array dimensions
      INTEGER, INTENT(OUT)          :: nx, ny            ! actual array dimensions
      DOUBLE PRECISION, DIMENSION(nnx, nny), INTENT(OUT) :: array
      LOGICAL, EXTERNAL             :: file_exist        ! existance file
      CHARACTER(LEN=200)            :: line              ! index cuurent line
      INTEGER                       :: iline             ! note total hour equals
                                                         ! number of DATA entries in
                                                         ! file
      DOUBLE PRECISION              :: x                 ! storage of value
      CHARACTER(LEN=100)            :: str, str1, str2   ! storage of strings
      INTEGER                       :: idebug, iformat   ! debug information

!-------------------------------------------------------
!     Station information first line
!-------------------------------------------------------
    CHARACTER(LEN=  5)            :: wban             ! 5 digit WBAN ID number
    CHARACTER(LEN= 22)            :: city             ! Station name
    CHARACTER(LEN=  2)            :: state            ! Postal abbreviation for the
                                                      ! State or country
    CHARACTER(LEN=  1)            :: lat              ! Latitude direction followed
                                                      ! by degrees and minutes
    CHARACTER(LEN=  1)            :: lon              ! Latitude direction followed
                                                      ! by degrees and minutes


!-------------------------------------------------------
!     Printout
!-------------------------------------------------------
      idebug = 0
!-------------------------------------------------------
!     Open file
!-------------------------------------------------------
```

```
    WRITE(0,*) '[read_tmy2]   START reading climate DATA file:
                 "',TRIM(ADJUSTL(filename)),'"'

!-----------------------------------------------------------
!     Read first line with station data
!----------------------------------------------------------

!.....some output
      IF (idebug==1) THEN
        PRINT *, 'WBAN ID#    =',wban
        PRINT *, 'city        =',city
        PRINT *, 'State       =',state
        PRINT *, 'Timezone    =',timezone
        PRINT *, 'Lat         =',lat
        PRINT *, 'Lat deg     =',lat_deg
        PRINT *, 'Lat min     =',lat_min
        PRINT *, 'Lon         =',lon
        PRINT *, 'Lon deg     =',lon_deg
        PRINT *, 'Lon min     =',lon_min
        PRINT *, 'Elevation   =',city_elev
      ENDIF

      GOTO 9999
 9000 WRITE(0,*) '[read_tmy2]   ERROR not existant file
                                 "',TRIM(ADJUSTL(filename)),'"'
      CALL merror(1)
 9001 WRITE(0,*) '[read_tmy2]   ERROR reading file "',TRIM(ADJUSTL(filename)),'"'
      CALL merror(1)
      CALL mwarning(1)
 9002 WRITE(0,*) '[read_tmy2]   WARNING no of climate DATA limited to "',nnx,'"
                                 entries, file "',TRIM(ADJUSTL(filename)),'"'
 9999 CONTINUE

      WRITE(0,*) '[read_tmy2]   Number of climate DATA entries    : "',iline
      WRITE(0,*) '[read_tmy2]   END reading climate DATA file:
                                 "',TRIM(ADJUSTL(filename)),'"'
      CLOSE(UNIT=1)

      END SUBROUTINE read_tm2
```

Example interface file 'sls.inp' (>700 variables)

```
!===========================================================
!
! Input file
!
! Format
! ------
! line is character string of size 200, containing following information
!
! [variable name] <type variable> = val1, val2, val3, ... , ...  ! comment
!
! Explanation format
! ------------------
! - If line starts with exclamation mark it is interpreted as a comment line and
!    skipped
! - Values are separated by colons ','
! - If no value is specified between two colons (e.g. ',,' or ',  ,')  this is
!    intepreted as value 0d0.
!
! Recognised types variable
! -------------------------
! type variable = 'dist'      (val1 to val8 :: real)
!   var1 = mean     ! mean value
!   var2 = min      ! min value
!   var3 = max      ! max value
!   var4 = def      ! default value
!   var5 = wht      ! weight factor %/year (obsolete)
!   var6 = dist     ! type distribution  (1d0=normal)
!   var7 = act      ! distribution active (0d0=no, 1d0=yes)
!   var8 = var      ! standard deviation
! type variable = 'value'      (val1 to val4 :: real)
!   var1 = val      ! actual value
!   var2 = min      ! min value
!   var3 = max      ! max value
!   var4 = def      ! default value
! type variable = 'string'    (val1 :: string length max 100, within quotes)
!
! Note about gases
! ----------------
! Gases in ascending order (1) H2O, (2) N2, (3) O2, (4) Ar, (5) Kr, (6) Xe, (7)
!   SF6, (8) gas1, (9) gas2, (10) gas3
!
! Flag
! ----
! In general "0d0" is interpreted as "False", and "1d0" is interpreted as "True "
!
!
! Distributed variable
! --------------------
! y0=prob(mean,var) for example normal distribution at start simulation
! yactual = y0 * (1 + timecoef*time)*(1+tempcoef*temp)
!
!===========================================================
!
!
!===========================================================
! MENU About
!===========================================================
  [i_version]    <value>  =  1.1d0, 1.1d0 , 1.1d0 , 1.1d0   ! [-] version number
                                                            ! SEALSIM
!===========================================================
! MENU Case description
!===========================================================
  [i_casename]   <string> = "case_tps_10-03-2003"           ! [-] name case
  [i_casedate]   <string> = "10-03-2003"                    ! [-] case creation
                                                            ! date
  [i_creator]    <string> = "Titus"                         ! [-] case creator
```

```
  [i_flag_class] <value>  = 0d0, 0d0, 1d0, 0d0            ! [-] flag design class
                                                          ! 0) TPS 1) Box-spacer
!===========================================================
! MENU Climate data
!===========================================================
  [i_file_clim]  <string> = "./94728.tm2"                 ! [-]   file with
                                                          ! climate data
  [i_flag_clim]  <value>  = 0d0, 0d0 , 1d0, 0d0           ! [-]   flag climate
                                                          ! repetition 0) no
                                                          ! 1)yes
  [i_clim_repeat] <value>  = 8760d0, 0d0, 9d9, 8760d0     ! [hr]  repeatal period
                                                          ! climate data
!-----------------------------------------------------------
  [i_flag_seal]   <value>  =   1d0,   0d0,   1d0,   0d0   ! [-]   Flag=0 calc,=1
                                                          ! from seal file
  [i_file_seal]   <string> = "./seal.txt"                 ! [-]   File, T/RH near
                                                          ! seal as function [hr]
```

Interrupt handling between GUI and Engine by GUI

Engine: "main.exe"
Input file: "sls.inp" (problem definition)
Output file: "sls.out" (results)
Output file: "sls.log" (log of status/warnings/errors)

Flag files generated by engine
"STARTED"
Exp l: Engine started
"RUNNING"
Exp l: contains 2 integers, indicating status calculations,
1st integer: status Monte Carlo runs 0-100%,
2nd integer simulation time 0-100%
Action GUI: show status bar, elapsed time 0-100%, Monte-Carlo runs 0-100%
"WARNING"
Exp l: generated in case of warning occurring. Reported in file "sls.log"
"ERROR"
Exp l: Fatal error. Engine stops. Flag file "FINISHED" is generated.
Action GUI: open window "sls.log".
"FINISHED"'
Exp l: Engine finished. IF "ERROR" does not exist, engine landed safely
"HALT"
Exp l: At end simulation all Monte Carlo runs, engine is halted, and waits for Flag file "MONTECARLO" to be generated by GUI, which contains an integer representing the number of additional Monte Carlo runs that the user wants to run.
Action GUI: If "HALT", ask user for number of additional Monte Carlo runs and generate "MONTECARLO"

GUI: Status bar indicating status calculations (Monte Carlo run, time elapsed)
"RUNNING" contains 2 integers,
1st integer: number of Monte Carlo runs out of total runs (0-100%)
2nd integer: time elapsed for specific Monte Carlo run: (0-100%)

GUI: Flag files generated
"PAUSE", Engine will pause until file "CONTINUE" is generated
"CONTINUE". Engine will continue
"STOP", Engine will stop

"MONTECARLO", Generated after file "HALT" is detected user

Generate engine.exe with Compaq Visual FORTRAN version 6.6B

Note: The source code files mentioned in this section are proprietary to the US Department of Energy and are not included in any distribution of this software. The *.DLL and engine.exe files are included in the distribution and are required to run SealSim 1.1.

1) Generate gasses.dll

- Menu File/New → Fortran Dynamic Link Library → project name gasses
- Menu Project/Add to Project/Files →
  - gasses.for
  - w5cog.fi (include file)
- Menu Project Settings, Tab: Fortran, Tab: Fortran Language → Force Free Form, Use File Extension (Do this for configuration release)
- Menu Build Configurations/Set Active Configuration → Release
- Menu Build → build gasses.dll (also builds gasses.lib)

Step 2 Generate "w5cog.dll"

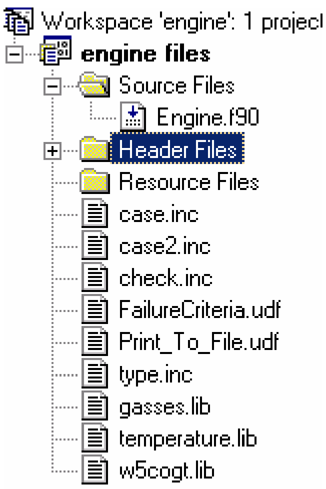
- Menu File/New → Fortran Dynamic Link Library → project name w5cog
- Menu Project/Add to Project/Files →
  - w5cog.v5.2.03.for
  - w5cog.fi
  - gasses.lib
- Menu Project/Settings Under tab Fortran, select Fortran Language, Force Free Form
- Menu Build Configurations/Set Active Configuration → Release
- Generate "w5cog.dll" (also builds w5cog.lib)

Step 2 Generate "temperature.dll"

- Menu File/New → Fortran Dynamic Link Library → project name temperature
- Menu Project/Add to Project/Files →
  - temperature.f90
- Menu Project/Settings Under tab Fortran, select Fortran Language, Force Free Form
- Menu Build Configurations/Set Active Configuration → Release
- Generate "temperature.dll" (also generates temperature.lib)

Step 3 Generate "Engine.exe"

- Open Workspace (Console Application). Note: Check option "This project will be linked against one or more Fortran DLL Import libraries"
- Menu Project/Add to Project/Files →
  - Engine.for
  - FailureCriteria.udf
  - Print_To_File.udf
  - w5cog.fi
  - case.inc
  - case2.inc
  - type.inc
  - check.inc
  - gasses.lib
  - w5cog.lib
  - temperature.lib
- Menu Project/Settings Under tab Fortran, select Fortran Language, Force Free Form
- Menu Build Configurations/Set Active Configuration → Release
- Generate "engine.exe"
- Place engine.exe together with gasses.dll, w5cogt.dll, temperature.dll in one directory



11 Appendix #3) Assumptions/Future release

Material properties

Specifics
- Function of temperature-time
- Probability shape function (mean and standard deviation)

Not provided in this version of SealSim 1.1, but are needed for full functionality
- Material properties (degradation) explicit functions of UV-exposure
- Material properties (degradation) explicit functions of liquid water-exposure (e.g. Glass transition temperature, E-D modulus)
- Effect of stress on permeation properties
- More detailed visco-elastic properties
- Filling of the database

Included in this phase
- Definition
- IGDB
- One DB

Geometry/spacer system

Specifics
- Spacer systems: Box-spacer, TPS spacer
- "parametric set-up" of predefined geometry
- Rectangular IGU, point symmetric.
- Model specific details: see elsewhere

Not provided in this version of SealSim 1.1, but are needed for other IG designs
- Other spacer systems than Box-spacer and TPS-spacer
- Connection 'seal' database

Climate conditions

Specifics
- TM2,
- TM2 format extended to give more possibilities to define climate conditions
- Climate next to seal, prescribed or equal to ambient

Not provided in this version of SealSim 1.1, but are needed for full functionality
- Other weather data formats
- Climate next to seal (influence frame etc).

Units

Specific
- SI Units
- SealSim 1.1 works with SI-Units
- Climate data files are in [degrees C]. Internally SealSim 1.1 works with [degrees K].

Not provided in this version of SealSim 1.1
- English Units (inches, pounds)

Documentation

Specific
- Work document
- First manual

Not provided in this version of SealSim 1.1, but are needed for full functionality
- Detailed User manual
- Detailed Programmers manual
- Context sensitive help

Probability distributions

Specific
- Normal probability distribution

Not provided in this version of SealSim 1.1, but are needed for full functionality
- Other types of distributions
- After each statistical evaluation, estimate number of additional simulation runs required to achieve a predefined accuracy for the output.

Models
- 1D Detail level geometry

Not provided in this version of SealSim 1.1, but are needed for full functionality
- 1.5D extensions
- 2D
- 3D
- Frame, sash model
- Coupling to other Database (functionality)
- Coupling to seal-database (future extension, translator)

Numerical

Specific
- Convergence stability, relaxation factors
- Speed versus clarity coding

Not provided in this version of SealSim 1.1, but are needed for full functionality
- Check if boundary conditions are resolved with respect to (numerical) time step
- Enhanced Speed of calculation
- Convergence criteria/restart

Testing/verification code

Specifics
- Sub-models

Not provided in this version of SealSim 1.1, but are needed for full functionality

- Additional sample problems with realistic values
- Simulated versus measured results from lab and field data

GUI

GUI, key features
- C# - .net framework
- Generic setup GUI: definition GUI by XML file
- Dynamic construction of UI-element from an easily editable XML files (no recompilation of UI).
- XML file defines variable tree, access database, help, min, max, etc.
- Thus variables can be added, etc. without re-compilation of GUI
- More flexible in long-term
- Connection to Glazing database
- Connection to SealSim 1.1 database with properties of all materials

Not provided in this version of SealSim 1.1
- Templates for glass, seals, climate-configurations, and simulation settings (e.g. to easily calculate with the same climates for different glass lites)
- Output, variables in time, balances, etc.
- Visual indication of glass color
- Help file
- Help per separate input field, context sensitive help
- Extended user input checks
- Editing of User-Database data from within SealSim 1.1

Gas Transport Model (H_2O, Ar, Kr, N_2 etc.)

Specifics
- Permeation of multiple gases
- Gases are in solution in polymer material
- Permeation through glass and metal spacers is not considered.
- Water vapor is a condensable gas, rest non-condensable
- Gas transport through seal "1-dimensional"
    - Permeation through 'intact' seal (inner & outer seal present): 1D (one dimensional) spatial differential equation
    - Permeation shortcuts of corners keys and gas fill holes (inner seal missing): 1D spatial differential equation for outer seal
    - Total permeation is combined permeation of 'intact' seal and 'not intact' seal weighted with seal perimeter
- Gas volume has uniform composition, the composition changes in time.
- Desiccant loading
    - Desiccant is present in polymer inner seal (TPS) or spacer bar (Box-spacer).
    - Desiccant beads behave the same
    - Desiccant adsorption/adsorption of gases (loading): Langmuir liquid loading ratio
    - Increased path length permeation due to desiccant in polymer
    - Holes are present in spacer, allowing mass-transfer between gas-space and desiccant present in spacer. It is assumed that the holes form no bottleneck for gas-transport.
- Equations
    - One dimensional permeation through intact seal (per gas) one dimensional spatial differential equation

- One dimensional permeation through not-intact seal (per gas) one dimensional spatial differential equation
- Mass balance of gases over gas space, one equation per gas
- Mass balance of gases desiccant, one equation per gas

Not provided in this version of SealSim 1.1
- Diffusion resistance holes in spacer bar
- Hydrocarbon out-gassing polymer, hydrocarbon adsorption & displacement effect of other gases.
- Gas transport material parameters are not considered to be a function of stress.
- Transport of vapors and gases along interfaces, rubber-glass, rubber-spacer.
- Not modelled is the reduction in time of the moisture or gas penetration path length, caused by adhesion/cohesion failure of the seal. Only the onset of a structural seal failure will be detected, after which it is implicitly concluded that the seal will also fail with respect to gas fill and internal condensation. The prime failure cause will be addressed as a structural failure.

Stress model

Specifics
- Small deflections are considered, that is the load situation does not change due to the deflections.
- Linear viscoelastic behaviour of the seal material is assumed.
- Seal, including wet seal is composed of a spring/dashpot system,
- Characteristic 2D (two dimensional) cross section is a transferred spring-dashpot system, where loads and deformations are in plane
- Glass lite deforms following an analytical function for a rectangular plate
- Barometric pressure loads, wind loads, etc., are specified via climate file TM2.
- No warping / torsion of the IGU and sash / window frame are considered.
- Local effects of setting blocks are not considered. No point loads are considered.
- The onset of an adhesion rupture or cohesion failure will be detected after which the simulation will stop. Crack propagation in time and the effect of reduced path length on gas transport is not studied.
- Sash dimensions are described, directly or implicitly via sash temperature & COTE.
- Thermal expansion of the spacer bar is assumed not to be restricted by the polymer.
- At time 'zero' no initial stress deformations are included in the time history
- Equations
  - Force balance for every degree of freedom (4 in x-direction, 4 in y-direction)
  - Includes plate equation for lites (load versus deflection)
- The normal loads originate from three sources:
  - The normal loads exerted by the glass window lites on the system which are due to the lite deflections in the lite thickness direction, i.e., Q_x^{iy} and Q_y^{ix}
  - The thermal expansion of the sash
  - The thermal expansions of the seals and spacer
- The shear loads can be attributed to three sources as well:
  - The shearing loads exerted by the glass window lites on the system due to the weight of the lites.
  - The differences in thermal expansion among the glass window lites, the sash, and the spacer.
  - The effect that the thermal expansion of the spacer at the longer side of the window 'pushes' (or 'pulls') the spacer on the shorter side; hence, the shorter spacer is displaced relative to the window lites.

Not provided in this version of SealSim 1.1
- More detailed dashpot/spring elements
- More than one-characteristic cross section
- Visco-elastic non-linear behaviour, tacking, etc.

- Detailed spatial resolution 2D-3D (two dimensional) or (three dimensional)
- Non rectangular geometries
- Point loads
- Initial stresses
- Warp/torsion
- Detailed load situations, also out of plane
- Glass transition temperature

Thermal model

Specifics

- The temperature of components is calculated from inside and outside climate conditions, heat transfer coefficient h, etc., and inside/outside climate conditions. Centre of glass calculation is used.
- No time history (effect of heat capacity) of materials is considered.

Not provided in this version of SealSim 1.1

- Time history
- Frame/edge effects
- Thermal radiation
- Coupling of SealSim 1.1 to / THERM

Units used in the Materials Database ‘**sealsim.mdb**.’

DessicantTable

Database Designation	Units	Description
BulkDensity	kg/m^3	
TrueDensity	kg/m^3	
TortuosityFactor	m/m	
BeadSize	m	
PoreSize	m	
Porosity	m^3/m^3	

GassesTable

Database Designation	Units	Description
GasMolWeight	kg/mol	
Cond_a	W/(m-K)	
Cond_b	$W/(m\text{-}K^2)$	
Cond_c	$W/(m\text{-}K^3)$	
DynVis_a	Pa s	
DynVis_b	Pa s/K	
DynVis_c	$Pa\ s/K^2$	
HeatCap_a	J/(kg-K)	
HeatCap_b	$J/(kg\text{-}K^2)$	
HeatCap_c	$J/(kg\text{-}K^3)$	

GasThroughDessicantProps

Database Designation	Units	Description
RefSorpT0	K	
RefSorpT1	K	
RefSorp0	1/Pa	
RefSorp1	1/Pa	
MaxLoad	kg/m^3	

GasThroughSealProps

Database Designation	Units	Description
RefTempSolubilityTS0	K	
RefTempSolubilityTS1	K	
SolubilityS0	$kg/(m^3\text{-}Pa)$	
SolubilityS1	$kg/(m^3\text{-}Pa)$	
RefTempPermeabilityTP0	K	
RefTempPermeabilityTP1	K	
PermeabilityP0	kg/(m-s-Pa)	
PermeabilityP1	kg/(m-s-Pa)	

PolymerMaterials

Database Designation	Units	Description
EffHeatConductivity	W/(m-K)	
HeatCapacity	J/(kg-K)	
Density	kg/m^3	
Emmisivity	"no units"	
CohesiveYieldStress	N/m^2	
CohesiveYieldStressRefTemp	K	
CohesiveYieldStressTempCoef	$N/(m^2$-K)	
CohesiveYieldStressTimeCoef	$N/(m^2$-yr)	
MinStrain	m/m	
MinStrainRefTemp	K	
MinStrainTempCoef	m/(m-K)	
MinStrainTimeCoef	m/(m-yr)	
MaxStrain	m/m	
MaxStrainRefTemp	K	
MaxStrainTempCoef	m/(m-K)	
MaxStrainTimeCoef	m/(m-yr)	
MaxShear	m/m	
MaxShearRefTemp	K	
MaxShearTempCoef	m/(m-K)	
MaxShearTimeCoef	m/(m-yr)	
YoungModulus	N/m^2	
YoungModulusRefTemp	K	
YoungModulusTempCoef	$N/(m^2$-K)	
YoungModulusTimeCoef	$N/(m^2$-yr)	
PoissonModulus	no units'	
PoissonModulusRefTemp	K	
PoissonModulusTempCoef	-'/K	
PoissonModulusTimeCoef	-'/yr	
LinearThermalExpansionCoef	m/(m-K)	
LinearThermalExpansionRefTemp	K	
LinearThermalExpansionTempCoef	$m/(m\text{-}K^2)$	
LinearThermalExpansionTimeCoef	m/(m-K-yr)	
DynamicViscosity	Pa-s	
DynamicViscosityRefTemp	K	
WLFglassTransitionTemp	K	
WLFconstantCG1	'no units'	
WLFconstantCG2	'no units'	

SolidMaterials

Database Designation	**Units**	**Description**
EffHeatConductivity	W/(m-K)	
HeatCapacity	J/(kg-K)	
Density	kg/m^3	
Emmisivity	"no units"	
CohesiveYieldStress	N/m^2	
CohesiveYieldStressRefTemp	K	
CohesiveYieldStressTempCoef	$N/(m^2$-K)	
CohesiveYieldStressTimeCoef	$N/(m^2$-yr)	
MinStrain	m/m	
MinStrainRefTemp	K	
MinStrainTempCoef	m/(m-K)	
MinStrainTimeCoef	m/(m-yr)	
MaxStrain	m/m	
MaxStrainRefTemp	K	
MaxStrainTempCoef	m/(m-K)	
MaxStrainTimeCoef	m/(m-yr)	
MaxShear	m/m	
MaxShearRefTemp	K	
MaxShearTempCoef	m/(m-K)	
MaxShearTimeCoef	m/(m-yr)	
YoungModulus	N/m^2	
YoungModulusRefTemp	K	
YoungModulusTempCoef	$N/(m^{2-}K)$	
YoungModulusTimeCoef	$N/(m^2$-yr)	
PoissonModulus	no units'	
PoissonModulusRefTemp	K	
PoissonModulusTempCoef	K^{-1}	
PoissonModulusTimeCoef	yr^{-1}	
LinearThermalExpansionCoef	m/(m-K)	
LinearThermalExpansionRefTemp	K	
LinearThermalExpansionTempCoef	$m/(m-K^2)$	
LinearThermalExpansionTimeCoef	m/(m-K-yr)	
SolarAbsorptionCoef	no units	

Appendix 4

Laboratory Test Data

	Summary		Failures										
	Tested	Pass	BP	V	NO	NR	InS	BR	Triples	Broke	ND	Oven	CK
Initial Seal	1915	1785	32	4	4	70	12	3	5				
High Heat/Humidity	950	910	2	9	11	4	3			2	6	3	
Temperature Cycle	910	887				2	4			12		1	4
Water/UV	887	838	6	2	2	10	19			3		4	3
Pressure Cycle	820	738	23	4	7	3	24			5		5	11

BP = Issues in the patch/4th corner issues
V = Voids in sealant coverage
NO = Cause of failure is not obvious
NR = No reason given
InS = Insufficient sealant
ND = No desiccant
BR = Duotech gas rivet issues
Oven = Issues with oven temp/pressure
CK = Corner key issues

Issued October 19, 2004

Year	Initial Seal		Failures						
	Tested	Pass	BP	V	NO	NR	InS	BR	Triples
2003	242	227	6	3	4	2			
2002	577	558	9			10			
2001	611	543	17	1		30	12	3	5
2000	485	457				28			

Year	High Heat/Humidity		Failures						
	Tested	Pass	BP	V	NO	NR	InS	Broke	ND
2003	254	243		1	8		1	1	
2002	340	329	1	3	2	4		1	
2001	356	338	1	5	1		2	1	6

Year	Temperature Cycle		Failures							
	Tested	Pass	BP	V	NO	NR	InS	Broke	Oven	CK
2003	243	237					2	4		
2002	329	322				1	2	3	1	
2001	338	328				1		5		4

Year	Water/UV		Failures							
	Tested	Pass	BP	V	NO	NR	InS	Broke	Oven	CK
2003	237	227					8	1		1
2002	322	300	5	1		6	9		1	
2001	328	311	1	1	2	4	2	2	3	2

Year	Pressure Cycle		Failures							
	Tested	Pass	BP	V	NO	NR	InS	Broke	Oven	CK
2003	227	194	1	1	5		18	4		4
2002	283	258	11	3	1	2	5		3	
2001	310	286	11		1	1	1	1	2	7

BP = Issues in the patch/4th corner issues
V = Voids in sealant coverage
NO = Cause of failure is not obvious
NR = No reason given
InS = Insufficient sealant
ND = No desiccant
BR = Duotech gas rivet issues
Oven = Issues with oven temp/pressure
CK = Corner key issues

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Appendix 5

Current IG Testing

Current IG Testing

(Includes tests accepted by testing-standards organizations (example ASTM) and tests commonly used by the industry and others to gain understanding and validate IG systems)

ASTM Standards for glass and IG units

- C148-95 Test Methods for Polariscope Examination of Glass Containers
- C158-95 Standard Test Methods for Strength of Flexure (Determination of Modulus of Rupture)
- C162-99 Standard Terminology of Glass and Glass Products
- C336 Test Method for Annealing Point and Strain Point of Glass by Fiber Elongation
- C338 Test Method for Softening Point of Glass
- C346 Test Method for 45-deg Specular Gloss of Ceramic Materials
- C698-93 Standard Test Method for Annealing Point and Strain Point of Glass by Beam Bending
- C717 Terminology of Building Seals and Sealants
- C724 Test Methods for Acid Resistance of Ceramic Decorations on Architectural-Type Glass
- C770-98 Standard Test Method for Measurement of Glass Stress Optical Coefficient
- C813-90 Standard Test Method for Hydrophobic Contamination on Glass by Contact Angle Measurement,
- C978-87 Standard Test Method for Photo-elastic Determination of Residual Stress in a Transparent Glass
- C1036 Standard Specification for Flat Glass

- C1045 Standard Practice for Calculating Thermal Transmission Properties Under Steady-State Conditions
- C1048-97 Standard Specification for Heat-Treated Flat Glass-Kind HS, Kind FT Coated and Uncoated Glass
- C1164 Practice for Evaluation of Limestone or Lime Uniformity from a Single Source
- C1172-96 Standard Specification for Laminated Architectural Flat Glass
- C1199 Standard Test Method for Measuring the Steady-State Thermal Transmittance of Fenestration Systems Using Hot Box Methods
- C1203 Specification for Flat Glass
- C1249-93 Standard Guide for Secondary Seal for Sealed Insulating Glass Units for Structural Sealant Glazing Applications
- C1265-94 Standard Test Method for Determining the Tensile Properties of an Insulating Glass Edge Seal for Structural Glazing Applications
- C1279-0 Standard Test Method for Non-Destructive Photo-elastic Measurement of Edge and Surface Stresses in Annealed, Heat-Strengthened, and Fully Tempered Flat Glass
- C1294-1 Standard Test Method for Compatibility of Insulating Glass Edge Sealants with Liquid-Applied Glazing Materials
- C1363-97 Standard Test Method for the Thermal Performance of Building Assemblies by Means of a Hot Box Apparatus
- C1369-97 Standard Specification for Secondary Edge Sealants for Structurally Glazed Insulating Glass Units
- C1376-97 Standard Specification for Pyrolytic and Vacuum Deposition Coatings on Glass
- C1392-0 Standard Guide for Evaluating Failure of Structural Sealant Glazing

- C1401-98 Standard Guide for Structural Sealant Glazing
- C1422-99 Standard Specification for Chemically Strengthened Flat Glass

- D1193 Specification for Reagent Water
- D2244 Test Method for Calculation of Color Differences from Instrumentally Measured Color Coordinates
- D2563-94 Standard Practice for Classifying Visual Defects in Glass-Reinforced Plastic Laminate Parts
- E4 Practices for Load Verification of Testing Machines
- E41 Definitions of Terms Relating to Conditioning
- E77 Test Method for Inspection and Verification of Thermometers
- E90-99 Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements
- E179 Guide for Selection of Geometric Conditions for Measurement of Reflection and Transmission Properties of Materials
- E283-91 Standard Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure Differences Across the Specimen
- E284 Terminology of Appearance
- E308 Practice for Computing the Colors of Objects by Using the CIE System
- E330-97 Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference

- E331-0 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference
- E380 Practice for Use of the International System of Units
- E405-89 Standard Test Methods for Wear Testing Rotary Operators for Windows
- E546-88 Standard Test Method for Frost Point of Sealed Insulating Glass Units
- E547-0 Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Cyclic Static Air Pressure Difference
- E576-88 Standard Test Method for Dew/Frost Point of Sealed Insulating Glass Units in Vertical Position
- E631 Terminology of Building Constructions
- E773-1 Standard Test Method for Accelerated Weathering of Sealed Insulating Glass Units
- E774-97 Standard Specification for the Classification of Durability of Sealed Insulating Glass Units
- E903 Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres
- E932 Practice for Describing and Measuring Performance of Dispersive Infrared Spectrophotometers
- E966-2 Standard Guide for Field Measurements of Airborne Sound Insulation of Building Facades and Facade Elements
- E971-88 Standard Practice for Calculation of Photometric Transmittance and Reflectance of Materials to Solar Radiation

- E987-88 Standard Test Methods for Deglazing Force of Fenestration Products
- E997-1 Standard Test Method for Structural Performance of Glass, in Exterior Windows, Curtain Walls, and Doors Under the Influence of Uniform Static Loads by Destructive Methods
- E998-84 Standard Test Method for Structural Performance of Glass in Windows, Curtain Walls, and Doors Under the Influence of Uniform Static Loads by Nondestructive Method
- E1017-88 Standard Specification for Generic Performance Requirements for Exterior Residential Window Assemblies
- E1105-0 Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Cyclic Static Air Pressure Difference
- E1175-87 Standard Test Method for Determining Solar or Photopic Reflectance, Transmittance, and Absorptance of Materials Using a Large Diameter Integrating Sphere
- E1233 Test Method for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Cyclic Static Air Pressure Differential
- E1300-0 Standard Practice for Determining Load Resistance of Glass in Buildings
- E1332-90 Standard Classification for Determination of Outdoor-Indoor Transmission Class
- E1376-90 Standard Test Method for Measuring the Interpose Attenuation of Sound Reflected by Wall Finishes and Furniture Panels
- E1423-99 Standard Practice for Determining the Steady State Thermal Transmittance of Fenestration Systems

- E1424-91 Standard Test Method for Determining the Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors Under Specified Pressure and Temperature Differences Across the Specimen
- E1425-91 Standard Practice for Determining the Acoustical Performance of Exterior Windows and Doors
- E1585-93 Standard Test Method for Measuring and Calculating Emittance for Architectural Flat Glass Products Using Spectrometric Measurements
- E1748-95 Standard Test Method for Evaluating the Engagement Between Windows and Insect Screens as an Integral System
- E1886-97 Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors, and Storm Shutters Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials
- E1887-97 Standard Test Method for Fog Determination
- E1996-1 Standard Specification for Performance of Exterior Windows, Curtain Walls, Doors and Storm Shutters Impacted by Windborne Debris in Hurricanes
- E2010-1 Standard Test Method for Positive Pressure Fire Tests of Window Assemblies
- E2025-99 Standard Test Method for Evaluating Fenestration Components and Assemblies for Resistance to Impact Energies
- E2068-0 Standard Test Method for Determination of Operating Force of Sliding Windows and Doors
- E2141-1 Standard Test Methods for Assessing the Durability of Absorptive Electrochromics Coatings on Sealed Insulating Glass Units
- E2188-2 Standard Test Method for Insulating Glass Unit Performance

- E2189-2 Standard Test Method for Testing Resistance to Fogging in Insulating Glass Units
- E2190-2 Standard Specification for Insulating Glass Unit Performance and Evaluation
- E6 P1 A proposed Recommended Practices for Testing Seal Longevity of Sealed Insulating Glass Units (Currently used by some manufacturers)
- E6 P2 A proposed Recommended Practices for Testing Seal Durability of Sealed Insulating Glass Units (This became E773 and E774 when approved)
- E6 P3 A proposed Specification for Sealed Insulated Glass Units (obsolete)
- F218 Test Method for Analyzing Stress in Glass
- F588-97 Standard Test Methods for Measuring the Forced Entry Resistance of Window Assemblies, Excluding Glazing Impact
- F801-96 Standard Test Method for Measuring Optical Angular Deviation of Transparent Parts
- F1758-96 Standard Test Methods for Detention Hinges Used on Detention-Grade Swinging Doors
- F1915-98 Standard Test Methods for Glazing for Detention Facilities
- F2090-1 Specification for Window Fall Prevention Devices With Emergency Escape (Egress) Release Mechanisms
- F2156-1 Standard Test Method for Measuring Optical Distortion in Transparent Parts Using Grid Line Slope

European Standards

- EN1279-1 Glass in Buildings Part 1 Generalities and dimensional tolerances
- EN1279-2 Glass in Buildings Part 2 Long term test method and requirements for moisture penetration
- EN1279-3 Glass in Buildings Part 3 Long term test method and requirements for gas leakage rate and for gas concentration tolerances
- EN1279-4 Glass in Buildings Part 4 Methods of test for the physical attributes of edge seals
- EN1279-5 Glass in Buildings Part 5 Evaluation of conformity
- EN1279-6 Glass in Buildings Part 6 Factory production control and periodic tests
- DIN1286-1 Sealed multiple glazing units Long-term performance
- DIN1286-2 Laminated insulating glass units Gas filled long-term performance tolerances on the gas volume content
- DIN52 293 Testing the tightness of gas-filled insulating glass units
- DIN52 294 Testing of glass Determination of loading of desiccants in insulating glass units
- DIN52 344 Testing the effect of alternating atmosphere on multi-layer insulating glass
- DIN52 345 Testing of glass Determination of dew point temperature of insulating glass units Laboratory test

Canadian Standards

- CAN/CSGB 12.1-M90 Tempered or laminated safety glass

- CAN/CSGB 12.10-M76 Glass, light and heat reflecting
- CAN/CSGB 12.11-M90 Wired safety glass
- CAN/CSGB 12.12-M90 Plastic safety glazing sheets
- CAN/CSGB 12.13-M91 Patterned glass
- CAN/CSGB 12.2-M91 Flat, clear sheet glass
- CAN/CSGB 12.20-M89 Structural design of glass for buildings
- CAN/CSGB 12.3-M91 Flat, clear float glass
- CAN/CSGB 12.4-M91 Heat absorbing glass
- CAN/CSGB 12.5-M96 Mirrors, silvered
- CAN/CSGB 12.6-M91 Transparent (one way) mirrors
- CAN/CSGB 12.8-M97 Insulating glass units
- CAN/CSGB 12.9-M91 Spandrel glass

Japanese Standards

- JIS R 3209 Seal Insulating Glass

French Standards

- NF P 78-451 Glazing and Mirror Insulating Glazing Units
  Moisture Penetration Resistance Tests

Appendix 6

Severity Factor Calculations

Severity Factor Calculations, Included Files

File List

1. **All6yr.xls.**

   File giving the average severity values for each station for the six year period of 1990 to 1995. Columns are:

   - Station
   - Location
   - State
   - Latitude
   - Longitude
   - Severity Total minimum
   - Severity Total maximum
   - Severity Total range
   - Vapor Pressure minimum
   - Vapor Pressure maximum
   - Vapor Pressure Sum
   - Hours of data

   Severity Total minimum ranges from -2.34 to +1.87 psi.

   Severity Total maximum ranges from 0.03 to +3.83 psi.

   Severity Total Range is from 0.465 to 3.395 psi.

   Vapor Pressure minimum ranges from 0.001 to 0.257 psi.

   Vapor Pressure maximum ranges from 0.238 to 0.541 psi.

   Vapor Pressure sum ranges from 362 to 3357 psi-hrs.

(Data is sorted in order of station number, contains one row for each station, 6 pages)

2. **All6yr2.xls.**

   The same data as in file 1 sorted in order of Severity Total.

   (Contains one row for each station, 6 pages)

3. **Allall.xls.**

   File giving the severity data on 262 stations in the US for 1990 through 1995. Data sorted on severity total. Columns are:

   - Station
   - Year
   - Severity Temperature
   - Severity Barometric Pressure
   - Severity Range Total
   - Vapor Pressure minimum
   - Vapor Pressure maximum
   - Vapor Pressure Sum
   - Hours of data.

Severity Temperature ranges from -2.518 to +2.020 psi.

Severity Barometric Pressure ranges from -0.077 to +3.900 psi.

Severity Total Range is from 0.374 to 4.798 psi.

Vapor Pressure ranges from 0.000 to 0.277 psi.

Vapor pressure maximum ranges from 0.219 to 0.655 psi.

Vapor pressure sum ranges from 349.4 to 3451.5 psi- hrs

(Contains one row for each station for each year, 4 pages)

4. **Altitude1.xls.**

   File showing atmospheric pressure at various altitudes. Pressures expressed in inch Hg, inch H2O, mbar, and psi. Original data from handbook in inches Hg Other values calculated.

5. **Durability_comparison.xls.**

   File lists comparison of test parameters of ASTM E773/E774, E2188, EN1279-2, and EN2179-3 tests. Severity values calculated for each test for temperature and the high humidity portion of the tests. Severity for humidity for the cycling portion of the ASTM tests can not be calculated due to differing conditions in different labs relating to details on how the test samples are mounted to the test wall.

   Temperature Severity:

   ASTM E773 and E774 varies from 603 to 1085 psi-hrs for the C to CBA rating

   ASTM E2188 has a level of 1120 psi-hrs

   EN2179-2 and EN1279-3 tests have values of 249 and 124 psi-hrs respectively.

   Time at Temperature:

   ASTM E773 and E774 – 78275 expressed in degree F-hrs

   ASTM E2188 – 80795 expressed in degree F-hrs

   EN2179-2 - 25361 expressed in degree F-hrs

EN2179-3 – 12681 expressed in degree F - hrs

Vapor Pressure Severity:

(CBA Rating)

ASTM E733 and 774 - 2767 psi – hrs

ASTM E2188 - 2767 psi – hrs

EN 1219-2 – 3095 psi – hrs

EN 1279 -3 – 1768 psi-hrs

The ASTM tests have a pass or fail metric based on internal dew point. EN2179-2 has a pass or fails metric based on calculation of moisture-penetration index, which is not easily converted to internal dew point. EN2179-3 has a pass or fail metric based end on maximum gas leakage of less than 1% per year.

6. **Durasum2.xls**

File shows a data summary for six years for Minneapolis (14922), for two years (1990 and 1992) for Miami (12839) and Boston (14739). This file shows yearly variations in severity figures for temperature, barometric pressure, and humidity as well as time at the conditions.

7. **maxtemphum.xls**

This file has the temperature and humidity summed as an indication of the relative rank of conditions which adversely affect IG life. The highest sums are for Guam and Puerto Rico while the lowest is for Bishop, California. The file also contains the average temperature and humidity for each station. Cooling degree days are summed for each station. Temperature and humidity minimum and maximums are included in the file. The file contains one line for each station for each year 1990 to 1995. (35 pages)

8. **Panama.xls**

(An example of a tropical climate with high temperatures and high humidity) Data is given for elevations of 1 meter and 40 meters in a rain forest climate on Barro Colorado Island in Gatun Lake. Vapor Pressure Severity is 3686 psi-hrs per year at 1 meter elevation and 3873 psi-hrs per year at 40 meter elevation. These values are higher than any data from the continental US.

9. **realtmy2.xls**

This file compares severity calculations for the actual NOAA weather data (1990 to 1995) with the TMY2 climate files. TMY2 files were created from actual weather station files by selecting specific months from various years that represented typical heating and cooling conditions. The files are intended for use with energy usage programs to give typical energy usage for each site. The months selected are not the most severe conditions.

Calculations of severity used the same program defaults for both sets of data. The NOAA severity data shown is the average for the six year period. The severity for temperature and vapor pressure has an average variation of less than 14%; however, individual stations have variations ranging from 45% to 236% for temperature and barometric pressure, 88% to 174% for vapor pressure sum. It is very important for durability work to use actual weather data so that the range of extreme conditions is included in the durability calculations. Stress and weather conditions are not considered to have a linear relationship in this study. (Data is sorted in state order, 10 pages)

10. smithsoniantables.xls

Data from the book "Smithsonian Meteorological Tables" Table 95 and 97 giving saturated vapor pressure of water over ice and water for temperatures from -160F to 212F, Vapor pressure is given in inch Hg., pressure (in psi) and parts per million (ppm) were calculated (1 page)

11. smithsoniantablesscondensed.xls

This is a condensed version of file # 10 with data given in 10 F degree increments. A column of %RH is included based on a dry bulb temperature of 75 F.

12. Stalist3.xls

This is a list of TMY2 data stations and their location with time zone, latitude, and longitude. Sorted in weather station number order, (6 pages)

13. stations.xls

This is the list of NOAA weather stations used for calculating IG severity conditions. (See the NOAA files in \docs for more information, 6 pages)

14. Stnigma.xls

This is a list of the locations used in the IGMA (SIGMA) long term IG study. Severity calculation results are shown for each location. Severity range for temperature and barometric pressure is from 1.383 to 2.708 psi. Vapor pressure sum average is from 842 to 2695 psi-hrs per year. Severity values are for the six years 1990 to 1995, 1 page.

15. sum_stn.xls

This file is a summary of all the stations for 1990 showing the Severity Total in psi and the Vapor Pressure exposure in psi and Vapor Pressure Sum in psi-hrs.

The number of valid data points in each file is also given.

Severity Total minimum is from -2.341 to 1.873 psi

Severity Total maximum is from 0.032 to 3.830 psi

Severity Total Range is from 0.465 to 3.395 psi.

Vapor Pressure minimum is 0.001 to 0.257 psi.

Vapor Pressure maximum ranges from 0.257 to 0.541 psi.

Vapor Pressure Sum ranges from 361.5 to 3356.9 psi- hrs.

Contains one row for each station, 6 pages

16. vpsort.xls

This file is the summary of Severity Total and Vapor Pressure Sum average values for six years from 1990 to 1995 and includes the color code information used for plotting the values of a map of the United States. The file is sorted in Vapor Pressure Sum order. A postscript format map is available in the file sevmap.ps for 11 x 17 pages.

17. weather.bas

This file is the Basic language program used to calculate the severity and vapor pressure values from the NOAA weather data. The program uses a file "vp.txt" to input a saturated vapor pressure table and temperature table. The file "stat.txt" contains the list of weather station data files to be analyzed. The program uses the uncompressed data files from NOAA. These files were placed in a directory that the weather program could read from. The output files were placed in a different directory. The weather program open file statements need to be modified for the file locations desired on the computer system being used for analysis. If other weather files are to be used for analysis the line input section should be modified to match the other weather files. Error lines are used in the analysis program to prevent missing or non-valid data from being placed in the output files. Each input data file has one line of data for each hour throughout the year. Output files are created for each hour (".tx2"), each month (".tx3"), and each year (".tx5").

GLHreport.doc/mldoll

Environmental Stress as a Factor in IG Durability, Phase I

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Keywords

1=environment 2=weather 3=sealantsystem 4=vaporpressure

Abstract

Environmental stress from local climatic conditions is believed to be a major element in insulated glass (IG) durability. Severity of climatic stress was examined for 262 locations in the United States. Equivalent atmospheric pressures were calculated to give a stress related severity factor. The same weather data was checked for vapor pressure severity. Severity of the applied stress is the first step in analyzing IG durability. Response of a given IG construction to that stress is the second step. Stress severity was found to vary over a range of 6 to 1 in the six years (1990 to 1995) of data examined.

Separation of the applied environmental stress from response to those conditions is a key element to accurately create appropriate accelerated durability tests. Assumptions and methods for analyzing the data are presented. Test development considerations will be discussed in a Phase II report. A similar range of stress conditions was found for locations in the former USSR. The methods described will allow this analysis to be made for Europe and other areas. The data results will lead to better understanding of regional variations in IG durability.

Introduction - Environment and Durability

A key to the successful application of an Insulating Glass (IG) unit in building construction is durability. The expectation of most building owners is that IG units should last for the life of the building. Unfortunately, that expectation is seldom met. The two lites of glass that make up the typical IG are assembled with a sealant that is subject to deterioration. An IG is subject to stresses from continually varying weather conditions as well as stresses from the building structure. In this paper I am going to address the weather conditions only.

The Main Text

The Problem

An IG unit contains an enclosed air space bounded by the spacer and sealant system and by the two lites of glass. Changes in temperature and air pressure cause variations in the internal pressure and volume in the enclosed air space. Each lite of the IG flexes from pressure variations and this motion causes stress in the sealant system that ultimately may cause total failure of the IG. An IG would make an excellent barometer if it were equipped with a device for measuring glass deflection and the temperature of internal air space.

Past work on IG durability testing has included methods for calculating glass flexing, internal pressures, and the resultant stresses. These past methods have carried the idea that the pressure difference across the sealant system was very small due to the change in internal volume of the enclosed air space as the glass flexes. The assumptions used typically included the sealant system as part of the problem definition.

I wished to evaluate the applied environmental stresses on the IG. The IG unit is exposed to a continually varying temperature and barometric pressure. This causes a cyclical stress loading on the sealant system. There is some indication that pressure cycling of an IG would be a useful addition to the repertory of IG testing. Pressure cycling is normally one of the top requirements for sealed mechanical systems that have a need to remain sealed throughout their lifetimes. The environment considered here is limited to that caused by temperature and barometric conditions surrounding the IG in the geographic location where it is installed. A later addition to the analysis added humidity as a factor important in providing vapor pressure stress across the sealant. There was a desire to clearly see how the effects of temperature and barometric pressure exposure varied in different geographical locations.

Separation of the problem elements

In this type of analysis, the first step is to separate the applied stress conditions from the response of the tested unit to those stresses. To meet this separation requirement the following conditions were assumed:

The IG was built at an altitude of sea level (1013 mbar) and a temperature of 70 F.
The IG has rigid glass with no perceptible flexing at the pressures encountered.
That the IG is desiccated to an initial internal dew point of -100 F.
The average internal air temperature is the average of the environmental weather temperature and 70 F, the interior building temperature, plus a factor of .15 for outdoor air movement. For example. with a given environment temperature difference, the calculated IG average temperature would equal the build temperature plus .65 times the temperature difference.

Given these assumptions, the perfect gas law can be used to describe the internal IG conditions at an environment temperature greater or lower than the initial IG build temperature. The calculated result is the pressure difference in pounds per square inch (psi) applied to the IG and caused by the exterior environment temperature and the calculated interior IG temperature. This pressure on an ideal IG with rigid walls is called the severity factor due to temperature, sevt, and is expressed in psi difference between the interior of the IG and the external environment.

The difference in barometric pressure in the environment to the barometric pressure at which the IG was sealed during assembly is called the severity due to barometric pressure, sevp, and is expressed in psi difference between the interior of the IG and the external environment. These two values are summed to determine the total severity, sevtotal, which also is expressed as the difference between the interior pressure of the IG and the external environment At times the sevt and sevp are additive and at other times they are opposing.

Method

To examine the environmental conditions at various locations, the CDROM of "Hourly United States Weather Observations 1990 - 1995" [1] was obtained. A set of working files was created which contained only the data needed for the analysis. The final working data files contained the weather station number, year, month, day, hour, dry bulb temperature, dew point temperature, humidity, and local station pressure (uncorrected for sea level). Missing data and errors were found in some files. A program was written to examine each line of each original source file for errors. Errors which were obvious were corrected in the set of working files. The final set of working files consisted of one file for each of the 262 weather stations for each of the years 1990 to 1995. A total of 1372 files, minus a few that lacked sufficient data for a valid analysis, were used to run the analysis. Analysis of reference [2] is planned to give additional data.

A program written in Quick Basic was written to carry out the severity calculations. The program allows changes in the initial assumptions to be made easily, and the results rerun. The program also calculated the heating and cooling degree days for each location. The original source files have weather data for each hour. An output file was created for each source file with one line of results for each hour. Each of the 8760 lines in the hourly files contain the following fields: station, year, month, day, hour, tdry, twet, humidity, station pressure, sevp, sevt, sevtotal, and vapor pressure.

Results

A daily summary file was also created for each source file with 365 lines. A third file was created for each source file with the calculated data summarized in twelve lines representing each month of the year. These files are large and are available on the CDROM [4] listed in the reference section.

The results show that significant geographical variations result from environmental applied stress. The final data summary of average minimum, maximum, and range of pressure severity values is on the CDROM. A short summary based on the yearly averages for each value is attached:

Lowest minimum severity, Barrow, Alaska, -2.34 psi
Highest minimum severity, Flagstaff, Arizona, +1.87 psi
Lowest maximum severity, Barrow, Alaska, +.03 psi
Highest maximum severity, Alamosa, Colorado, +3.83 psi , (elevation 2297 meters)
Lowest range in severity, San Juan, PR, +.46 psi
Highest range in severity, Talketna, Alaska, +3.39 psi

It was noted that the severity values changed significantly over relatively short distances. Construction of a map of isobars would be worthwhile for areas of the country of interest. This same approach can be applied to weather data from Europe, for example, to evaluate differences in IG stress.

The cyclical nature of the severity data can be clearly seen when the data is plotted on a strip chart recorder.

Vapor Pressure

The preceding analysis focused on the physical stress placed on the IG sealant system. Another factor in IG durability is the ability of the sealant system to withstand the vapor pressure differential between the environment and the desiccated interior air space. An IG is determined to have failed when the interior dew point rises to -20 F. Water vapor penetration (MVTR) of sealants is measured under fixed test conditions and is given a MVTR value which is dependent on the sealant temperature as well as specific test conditions and the specific path length of the sealant. Moisture vapor transport through a sealant is a time and material condition related event. Variations on vapor pressure differential, temperature, material stress, and material thickness affect the rate of vapor penetration,

The procedure used to evaluate the vapor pressure severity applied to the sealant system in this work is to convert the dry bulb environmental temperature and relative humidity into vapor pressure in psia. Relative humidity is the ratio of the vapor pressure at a given wet bulb temperature to the vapor pressure of saturated air at the dry bulb temperature. The sealant is exposed to the difference in the vapor pressure of the environment at a given time to the interior vapor pressure of the sealed air space

The Smithsonian Meteorological Tables [3] were used as a standard reference for the saturated vapor pressure at a given temperature. Specific values of dry bulb temperature and relative humidity from the weather data were used to calculate the vapor pressure difference between the environment and the interior of the IG. Since the IG is exposed to environmental conditions throughout its life, each hour of data produced a pressure difference that was then summed over time to represent the psi-hr total exposure severity being applied over time to the IG.

As the temperature and humidity vary hour by hour, the severity also varies. A plot of the severity shows a similar cyclical pattern as the severity of temperature and barometric pressure previously described. Hourly, monthly, and yearly summaries were calculated for each of the weather station locations described for each of the years 1990 to 1995. The total severity values expressed in psi-hrs ranged from 349 (Big Delta, Alaska) to 3451 (San Juan, PR) per year. One of the common tests conducted on IG units is known as the P-1 test. This test is currently not part of the ASTM standards, but is used by various IG manufacturers. One week in the P-1 chamber at 140 F and 95% humidity results in 461 psi-hrs of vapor pressure severity.

Vapor pressure severity of the ASTM E-773 and E-774 IG rating tests can not easily be calculated due to variations in mounting of the test samples to the test walls in various labs.

Conclusions - Environmental temperature and barometric pressure

The severity values calculated will be useful in studying the stresses that the sealant system must withstand to operate for the desired time in a given environment. Observing the response of the glass and sealant system with the IG unit in a pressure chamber may give the observer data that can not easily be measured in the field. Simulation of temperature conditions and barometric pressure variations in a lab will give data that are unattainable in an uncontrolled environment. A pressure chamber, similar to a hyperbaric chamber, would allow the observer to study the unit closely under varying load conditions.. The pressures differences calculated above are no greater than those involved with a change in altitude of 10000 feet and indeed are what the local inhabitants are exposed to on a yearly basis..

The applied environmental severity stress is higher than a casual view of the problem anticipated. The applied severity causes flexing of the glass and the sealant system which results in significant movement and stress in the sealant.

The second application of this analysis is to clearly show the cyclical nature of pressures and stresses that an IG unit experiences from changes in the environment. For an IG to have a durability of 10 to 20 years or more, it must be able to survive this cyclical loading without loss to its seal. The present IG tests used for certification purposes are an attempt to provide a measure of performance. To achieve longer durability will require new tests that more closely represent actual life conditions. The variations found in the environmental severity also lead one to expect that various sealant system designs might well be suited for different geographical locations.

Phase 2 of this project is planned for the use of this data in developing accelerated test methods that may be used to evaluate sealants, spacers, sealant systems, material specifications, and process methods. One goal of the new test methods is to produce a reliability index value that will accurately predict lung term durability of IG units.

Conclusions - Vapor pressure

Published data on MVTR for common IG sealants is based on static testing at a constant vapor stress with the sealant in a zero physical stress condition. The effect of varying sealant tensile stress and cycling vapor pressure stress would be valuable information for IG designers. .

The present IG test methods do not expose the unit to the combination of vapor pressure and time that is representative of many geographical locations. Increases severity in testing is needed to develop test results that may be used to calculate long term durability in those locations that have high combined psi-hrs stress. Examination of the detailed data shows that differing conditions may indicate that various sealant systems may be adequate for some locations, but not others.

References:

Weather Data

[1] Hourly United States Weather Observations 1990 - 1995 , a CDROM published by NOAA, Unites States Dept. of Commerce, Washington, DC, USA

[2] Solar and Meteorological Surface Observation Network, 1961 - 1990, version 1, September, 1993, a CDROM set published by NOAA, Unites States Dept. of Commerce, Washington, DC, USA

[3] Smithsonian Meteorological Tables, 6th revised edition, 1966, Smithsonian Institution

[4] A CDROM is available from the author containing the following files:
A list of the weather stations from the NOAA CD
A sample of several of the raw data files from the NOAA CD
Copy of the program used to validate the raw data
Copy of the program used to calculate the severity data
Copies of all of the extracted analysis runs for hourly, monthly, and yearly periods
Copy of the composite output yearly output file in Excel format (3.5 Mbytes)
A readme.txt file with the latest information
Contact the author at: Gerald Hendrickson, PE, Aspen Research Corp,1700 Buerkle Road, White Bear Lake, MN 55110 , USA
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ASTM E773, E774										
hour	start	end	F/minute	BTU/min		water	UV			
1	75	-20	1.583333							
2	-20	-20	0							
3	-20	75	-1.58333							
4	75	135	-1			first 1/2	On			
5	135	135	0				On			
6	135	75	1				On			
1	75	-20								
mass at temperature										
sp heat of mass										
air volume										
wall u value										

Severity calculation			Unit built at 1013 mbar and 70 F, tested at 1013 mbar							
	start	end	start	end	start	end				
	F	F	ave F	ave F	delta psi	delta psi				
1	75	-20	72.5	25	14.76934	13.45189	0.06934	-1.24811		
2	-20	-20	25	25	13.45189	13.45189	-1.24811	-1.24811		
3	-20	75	25	72.5	13.45189	14.76934	-1.24811	0.06934		
4	75	135	72.5	102.5	14.76934	15.60142	0.06934	0.901415		
5	135	135	102.5	102.5	15.60142	15.60142	0.901415	0.901415		
6	135	75	102.5	72.5	15.60142	14.76934	0.901415	0.06934		
1	75	-20	72.5	25	14.76934	13.45189	0.06934	-1.24811		
						min	-1.24811			
						max	0.901415			
1	75	-20	72.65	25.15	14.7735	13.45605	0.0735	-1.24395		
2	-20	-20	25.15	25.15	13.45605	13.45605	-1.24395	-1.24395		
3	-20	75	25.15	72.65	13.45605	14.7735	-1.24395	0.0735		
4	75	135	72.65	102.65	14.7735	15.60558	0.0735	0.905575		
5	135	135	102.65	102.65	15.60558	15.60558	0.905575	0.905575		
6	135	75	102.65	72.65	15.60558	14.7735	0.905575	0.0735		
1	75	-20	72.65	25.15	14.7735	13.45605	0.0735	-1.24395		
						min	-1.24395			
						max	0.905575			
	2188		2188	2188			733		733	733
0	75.00		0			0	75.00		0	
1	73.42		1.583333			1	73.42		1.583333	
2	71.83		3.166667			2	71.83		3.166667	
3	70.25		4.75			3	70.25		4.75	
4	68.67		6.333333			4	68.67		6.333333	
5	67.08		7.916667			5	67.08		7.916667	
6	65.50		9.5			6	65.50		9.5	
7	63.92		11.08333			7	63.92		11.08333	
8	62.33		12.66667			8	62.33		12.66667	
9	60.75		14.25			9	60.75		14.25	
10	59.17		15.83333			10	59.17		15.83333	
11	57.58		17.41667			11	57.58		17.41667	
12	56.00		19			12	56.00		19	
13	54.42		20.58333			13	54.42		20.58333	
14	52.83		22.16667			14	52.83		22.16667	
15	51.25		23.75			15	51.25		23.75	
16	49.67		25.33333			16	49.67		25.33333	

17	48.08		26.91667			17	48.08		26.91667	
18	46.50		28.5			18	46.50		28.5	
19	44.92		30.08333			19	44.92		30.08333	
20	43.33		31.66667			20	43.33		31.66667	
21	41.75		33.25			21	41.75		33.25	
22	40.17		34.83333			22	40.17		34.83333	
23	38.58		36.41667			23	38.58		36.41667	
24	37.00		38			24	37.00		38	
25	35.42		39.58333			25	35.42		39.58333	
26	33.83		41.16667			26	33.83		41.16667	
27	32.25		42.75			27	32.25		42.75	
28	30.67		44.33333			28	30.67		44.33333	
29	29.08		45.91667			29	29.08		45.91667	
30	27.50		47.5			30	27.50		47.5	
31	25.92		49.08333			31	25.92		49.08333	
32	24.33		50.66667			32	24.33		50.66667	
33	22.75		52.25			33	22.75		52.25	
34	21.17		53.83333			34	21.17		53.83333	
35	19.58		55.41667			35	19.58		55.41667	
36	18.00		57			36	18.00		57	
37	16.42		58.58333			37	16.42		58.58333	
38	14.83		60.16667			38	14.83		60.16667	
39	13.25		61.75			39	13.25		61.75	
40	11.67		63.33333			40	11.67		63.33333	
41	10.08		64.91667			41	10.08		64.91667	
42	8.50		66.5			42	8.50		66.5	
43	6.92		68.08333			43	6.92		68.08333	
44	5.33		69.66667			44	5.33		69.66667	
45	3.75		71.25			45	3.75		71.25	
46	2.17		72.83333			46	2.17		72.83333	
47	0.58		74.41667			47	0.58		74.41667	
48	-1.00		76			48	-1.00		76	
49	-2.58		77.58333			49	-2.58		77.58333	
50	-4.17		79.16667			50	-4.17		79.16667	
51	-5.75		80.75			51	-5.75		80.75	
52	-7.33		82.33333			52	-7.33		82.33333	
53	-8.92		83.91667			53	-8.92		83.91667	
54	-10.50		85.5			54	-10.50		85.5	
55	-12.08		87.08333			55	-12.08		87.08333	
56	-13.67		88.66667			56	-13.67		88.66667	
57	-15.25		90.25			57	-15.25		90.25	
58	-16.83		91.83333			58	-16.83		91.83333	
59	-18.42		93.41667			59	-18.42		93.41667	
60	-20.00		95			60	-20.00		95	
61	-20.00		95			61	-20.00		95	

62	-20.00		95			62	-20.00		95	
63	-20.00		95			63	-20.00		95	
64	-20.00		95			64	-20.00		95	
65	-20.00		95			65	-20.00		95	
66	-20.00		95			66	-20.00		95	
67	-20.00		95			67	-20.00		95	
68	-20.00		95			68	-20.00		95	
69	-20.00		95			69	-20.00		95	
70	-20.00		95			70	-20.00		95	
71	-20.00		95			71	-20.00		95	
72	-20.00		95			72	-20.00		95	
73	-20.00		95			73	-20.00		95	
74	-20.00		95			74	-20.00		95	
75	-20.00		95			75	-20.00		95	
76	-20.00		95			76	-20.00		95	
77	-20.00		95			77	-20.00		95	
78	-20.00		95			78	-20.00		95	
79	-20.00		95			79	-20.00		95	
80	-20.00		95			80	-20.00		95	
81	-20.00		95			81	-20.00		95	
82	-20.00		95			82	-20.00		95	
83	-20.00		95			83	-20.00		95	
84	-20.00		95			84	-20.00		95	
85	-20.00		95			85	-20.00		95	
86	-20.00		95			86	-20.00		95	
87	-20.00		95			87	-20.00		95	
88	-20.00		95			88	-20.00		95	
89	-20.00		95			89	-20.00		95	
90	-20.00		95			90	-20.00		95	
91	-20.00		95			91	-20.00		95	
92	-20.00		95			92	-20.00		95	
93	-20.00		95			93	-20.00		95	
94	-20.00		95			94	-20.00		95	
95	-20.00		95			95	-20.00		95	
96	-20.00		95			96	-20.00		95	
97	-20.00		95			97	-20.00		95	
98	-20.00		95			98	-20.00		95	
99	-20.00		95			99	-20.00		95	
100	-20.00		95			100	-20.00		95	
101	-20.00		95			101	-20.00		95	
102	-20.00		95			102	-20.00		95	
103	-20.00		95			103	-20.00		95	
104	-20.00		95			104	-20.00		95	
105	-20.00		95			105	-20.00		95	
106	-20.00		95			106	-20.00		95	

107	-20.00		95			107	-20.00		95	
108	-20.00		95			108	-20.00		95	
109	-20.00		95			109	-20.00		95	
110	-20.00		95			110	-20.00		95	
111	-20.00		95			111	-20.00		95	
112	-20.00		95			112	-20.00		95	
113	-20.00		95			113	-20.00		95	
114	-20.00		95			114	-20.00		95	
115	-20.00		95			115	-20.00		95	
116	-20.00		95			116	-20.00		95	
117	-20.00		95			117	-20.00		95	
118	-20.00		95			118	-20.00		95	
119	-20.00		95			119	-20.00		95	
120	-20.00		95			120	-20.00		95	
121	-18.42		93.41667			121	-18.42		93.41667	
122	-16.83		91.83333			122	-16.83		91.83333	
123	-15.25		90.25			123	-15.25		90.25	
124	-13.67		88.66667			124	-13.67		88.66667	
125	-12.08		87.08333			125	-12.08		87.08333	
126	-10.50		85.5			126	-10.50		85.5	
127	-8.92		83.91667			127	-8.92		83.91667	
128	-7.33		82.33333			128	-7.33		82.33333	
129	-5.75		80.75			129	-5.75		80.75	
130	-4.17		79.16667			130	-4.17		79.16667	
131	-2.58		77.58333			131	-2.58		77.58333	
132	-1.00		76			132	-1.00		76	
133	0.58		74.41667			133	0.58		74.41667	
134	2.17		72.83333			134	2.17		72.83333	
135	3.75		71.25			135	3.75		71.25	
136	5.33		69.66667			136	5.33		69.66667	
137	6.92		68.08333			137	6.92		68.08333	
138	8.50		66.5			138	8.50		66.5	
139	10.08		64.91667			139	10.08		64.91667	
140	11.67		63.33333			140	11.67		63.33333	
141	13.25		61.75			141	13.25		61.75	
142	14.83		60.16667			142	14.83		60.16667	
143	16.42		58.58333			143	16.42		58.58333	
144	18.00		57			144	18.00		57	
145	19.58		55.41667			145	19.58		55.41667	
146	21.17		53.83333			146	21.17		53.83333	
147	22.75		52.25			147	22.75		52.25	
148	24.33		50.66667			148	24.33		50.66667	
149	25.92		49.08333			149	25.92		49.08333	
150	27.50		47.5			150	27.50		47.5	
151	29.08		45.91667			151	29.08		45.91667	

152	30.67		44.33333			152	30.67		44.33333	
153	32.25		42.75			153	32.25		42.75	
154	33.83		41.16667			154	33.83		41.16667	
155	35.42		39.58333			155	35.42		39.58333	
156	37.00		38			156	37.00		38	
157	38.58		36.41667			157	38.58		36.41667	
158	40.17		34.83333			158	40.17		34.83333	
159	41.75		33.25			159	41.75		33.25	
160	43.33		31.66667			160	43.33		31.66667	
161	44.92		30.08333			161	44.92		30.08333	
162	46.50		28.5			162	46.50		28.5	
163	48.08		26.91667			163	48.08		26.91667	
164	49.67		25.33333			164	49.67		25.33333	
165	51.25		23.75			165	51.25		23.75	
166	52.83		22.16667			166	52.83		22.16667	
167	54.42		20.58333			167	54.42		20.58333	
168	56.00		19			168	56.00		19	
169	57.58		17.41667			169	57.58		17.41667	
170	59.17		15.83333			170	59.17		15.83333	
171	60.75		14.25			171	60.75		14.25	
172	62.33		12.66667			172	62.33		12.66667	
173	63.92		11.08333			173	63.92		11.08333	
174	65.50		9.5			174	65.50		9.5	
175	67.08		7.916667			175	67.08		7.916667	
176	68.67		6.333333			176	68.67		6.333333	
177	70.25		4.75			177	70.25		4.75	
178	71.83		3.166667			178	71.83		3.166667	
179	73.42		1.583333			179	73.42		1.583333	
180	75.00		0	0		180	75.00		0	0
181	76.08			1.083333		181	76.00			1
182	77.17			2.166667		182	77.00			2
183	78.25			3.25		183	78.00			3
184	79.33			4.333333		184	79.00			4
185	80.42			5.416667		185	80.00			5
186	81.50			6.5		186	81.00			6
187	82.58			7.583333		187	82.00			7
188	83.67			8.666667		188	83.00			8
189	84.75			9.75		189	84.00			9
190	85.83			10.83333		190	85.00			10
191	86.92			11.91667		191	86.00			11
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193	89.08			14.08333		193	88.00			13
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196	92.33			17.33333		196	91.00			16

197	93.42			18.41667		197	92.00			17
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205	102.08			27.08333		205	100.00			25
206	103.17			28.16667		206	101.00			26
207	104.25			29.25		207	102.00			27
208	105.33			30.33333		208	103.00			28
209	106.42			31.41667		209	104.00			29
210	107.50			32.5		210	105.00			30
211	108.58			33.58333		211	106.00			31
212	109.67			34.66667		212	107.00			32
213	110.75			35.75		213	108.00			33
214	111.83			36.83333		214	109.00			34
215	112.92			37.91667		215	110.00			35
216	114.00			39		216	111.00			36
217	115.08			40.08333		217	112.00			37
218	116.17			41.16667		218	113.00			38
219	117.25			42.25		219	114.00			39
220	118.33			43.33333		220	115.00			40
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222	120.50			45.5		222	117.00			42
223	121.58			46.58333		223	118.00			43
224	122.67			47.66667		224	119.00			44
225	123.75			48.75		225	120.00			45
226	124.83			49.83333		226	121.00			46
227	125.92			50.91667		227	122.00			47
228	127.00			52		228	123.00			48
229	128.08			53.08333		229	124.00			49
230	129.17			54.16667		230	125.00			50
231	130.25			55.25		231	126.00			51
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238	137.83			62.83333		238	133.00			58
239	138.92			63.91667		239	134.00			59
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241	140.00			65		241	135.00			60

242	140.00			65		242	135.00			60
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298	140.00			65		298	135.00			60
299	140.00			65		299	135.00			60
300	140.00			65		300	135.00			60
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302	137.83			62.83333		302	133.00			58
303	136.75			61.75		303	132.00			57
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305	134.58			59.58333		305	130.00			55
306	133.50			58.5		306	129.00			54
307	132.42			57.41667		307	128.00			53
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310	129.17			54.16667		310	125.00			50
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316	122.67			47.66667		316	119.00			44
317	121.58			46.58333		317	118.00			43
318	120.50			45.5		318	117.00			42
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321	117.25			42.25		321	114.00			39
322	116.17			41.16667		322	113.00			38
323	115.08			40.08333		323	112.00			37
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325	112.92			37.91667		325	110.00			35
326	111.83			36.83333		326	109.00			34
327	110.75			35.75		327	108.00			33
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331	106.42			31.41667		331	104.00			29

332	105.33			30.33333		332	103.00			28
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336	101.00			26		336	99.00			24
337	99.92			24.91667		337	98.00			23
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339	97.75			22.75		339	96.00			21
340	96.67			21.66667		340	95.00			20
341	95.58			20.58333		341	94.00			19
342	94.50			19.5		342	93.00			18
343	93.42			18.41667		343	92.00			17
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345	91.25			16.25		345	90.00			15
346	90.17			15.16667		346	89.00			14
347	89.08			14.08333		347	88.00			13
348	88.00			13		348	87.00			12
349	86.92			11.91667		349	86.00			11
350	85.83			10.83333		350	85.00			10
351	84.75			9.75		351	84.00			9
352	83.67			8.666667		352	83.00			8
353	82.58			7.583333		353	82.00			7
354	81.50			6.5		354	81.00			6
355	80.42			5.416667		355	80.00			5
356	79.33			4.333333		356	79.00			4
357	78.25			3.25		357	78.00			3
358	77.17			2.166667		358	77.00			2
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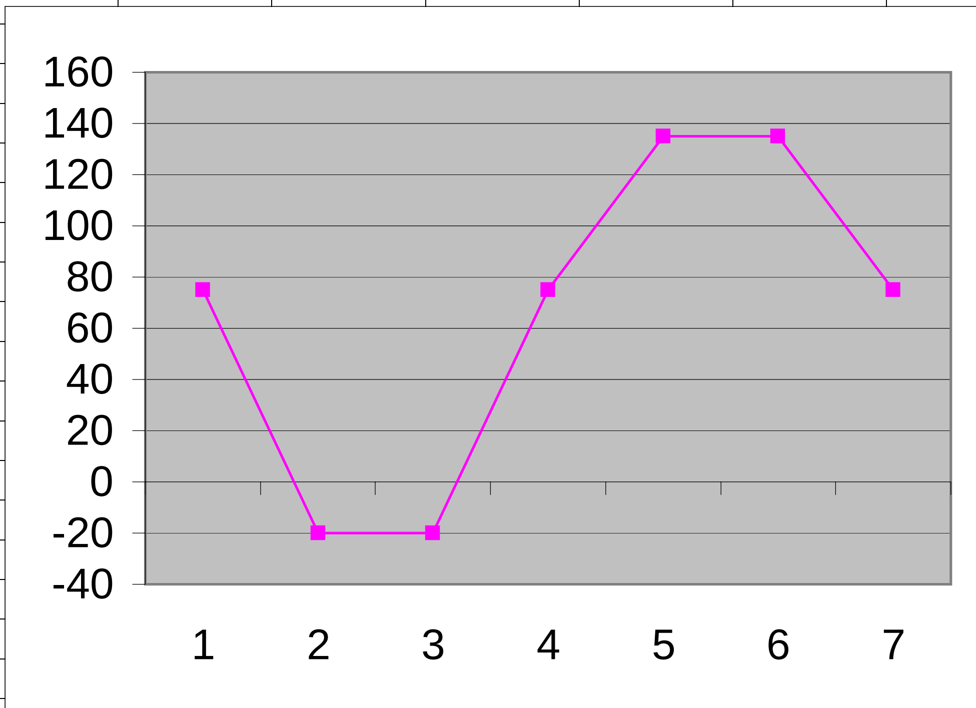
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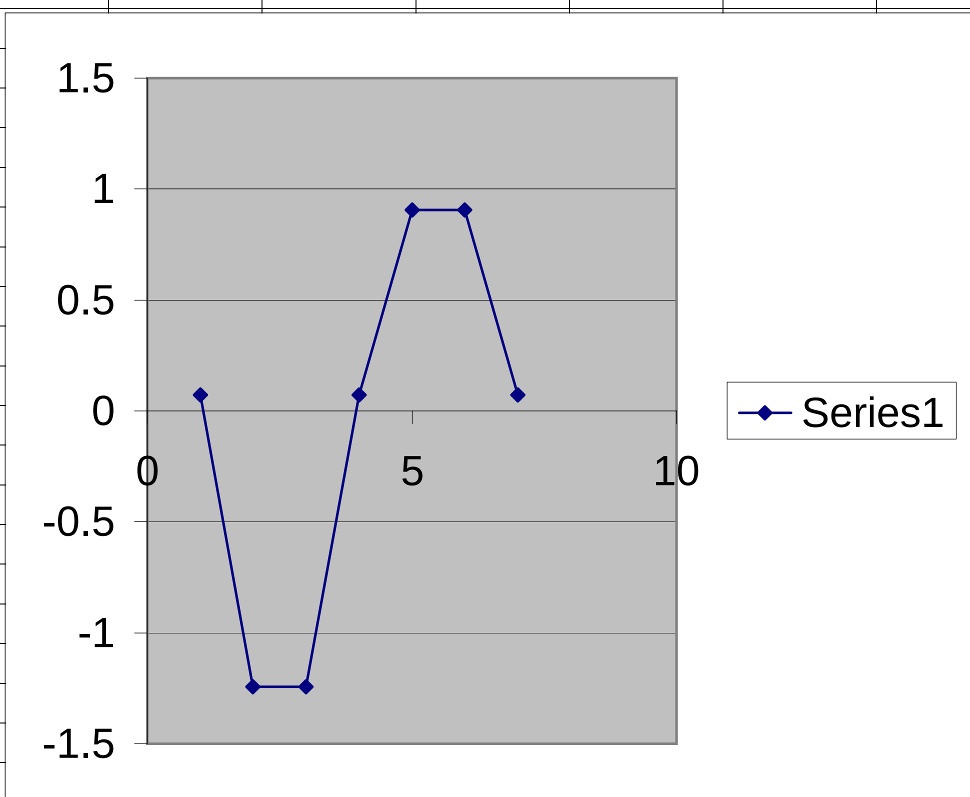
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-0.5
-1
-1.5
0
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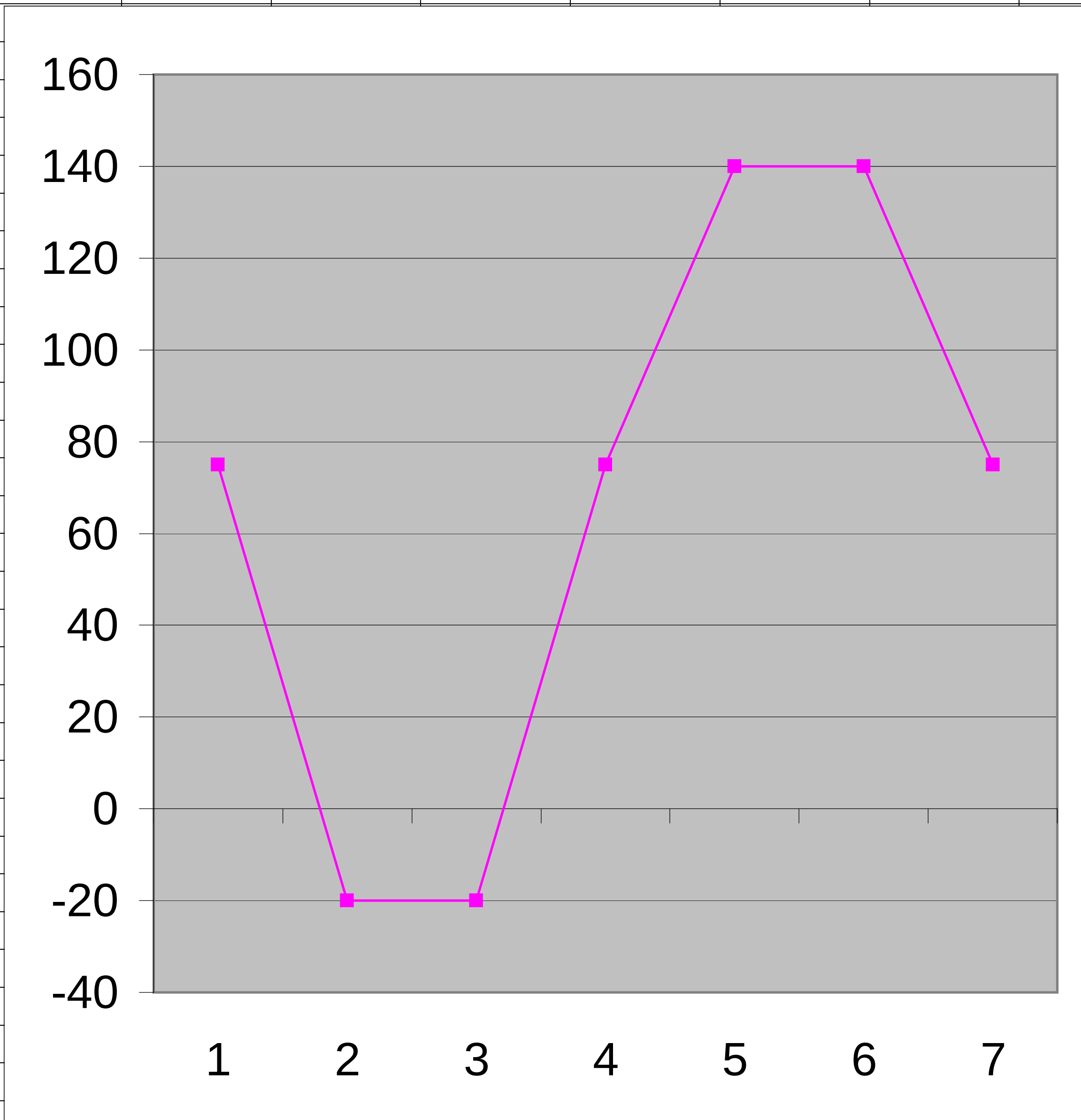
10
Series1

ASTM 2188, 2189, 2190									
hour	start	end	F/minute	BTU/min		water	UV		
1	75	-20	1.583333						
2	-20	-20	0						
3	-20	75	-1.58333						
4	75	140	-1.08333			first 1/2	On		
5	140	140	0				On		
6	140	75	1.083333				On		
1	75	-20							
mass at temperature									
sp heat of mass									
air volume									
wall u value									

Severity calculation			Unit built at 1013 mbar and 70 F, tested at 1013 mbar						
	start	end	start	end	start	end			
	F	F	ave F	ave F	delta psi	delta psi			
1	75	-20	72.50	25.00	14.76934	13.45189	0.06934	-1.24811	
2	-20	-20	25.00	25.00	13.45189	13.45189	-1.24811	-1.24811	
3	-20	75	25.00	72.50	13.45189	14.76934	-1.24811	0.06934	
4	75	140	72.50	105.00	14.76934	15.67075	0.06934	0.970755	
5	140	140	105.00	105.00	15.67075	15.67075	0.970755	0.970755	
6	140	75	105.00	72.50	15.67075	14.76934	0.970755	0.06934	
1	75	-20	72.50	25.00	14.76934	13.45189	0.06934	-1.24811	
						min	-1.24811		
						max	0.970755		
1	75	-20	72.65	25.15	14.7735	13.45605	0.0735	-1.24395	
2	-20	-20	25.15	25.15	13.45605	13.45605	-1.24395	-1.24395	
3	-20	75	25.15	72.65	13.45605	14.7735	-1.24395	0.0735	
4	75	140	72.65	105.15	14.7735	15.67492	0.0735	0.974915	
5	140	140	105.15	105.15	15.67492	15.67492	0.974915	0.974915	
6	140	75	105.15	72.65	15.67492	14.7735	0.974915	0.0735	
1	75	-20	72.65	25.15	14.7735	13.45605	0.0735	-1.24395	
						min	-1.24395		
						max	0.974915		
1	140	140	140	140	16.64151	16.64151	1.941509	1.941509	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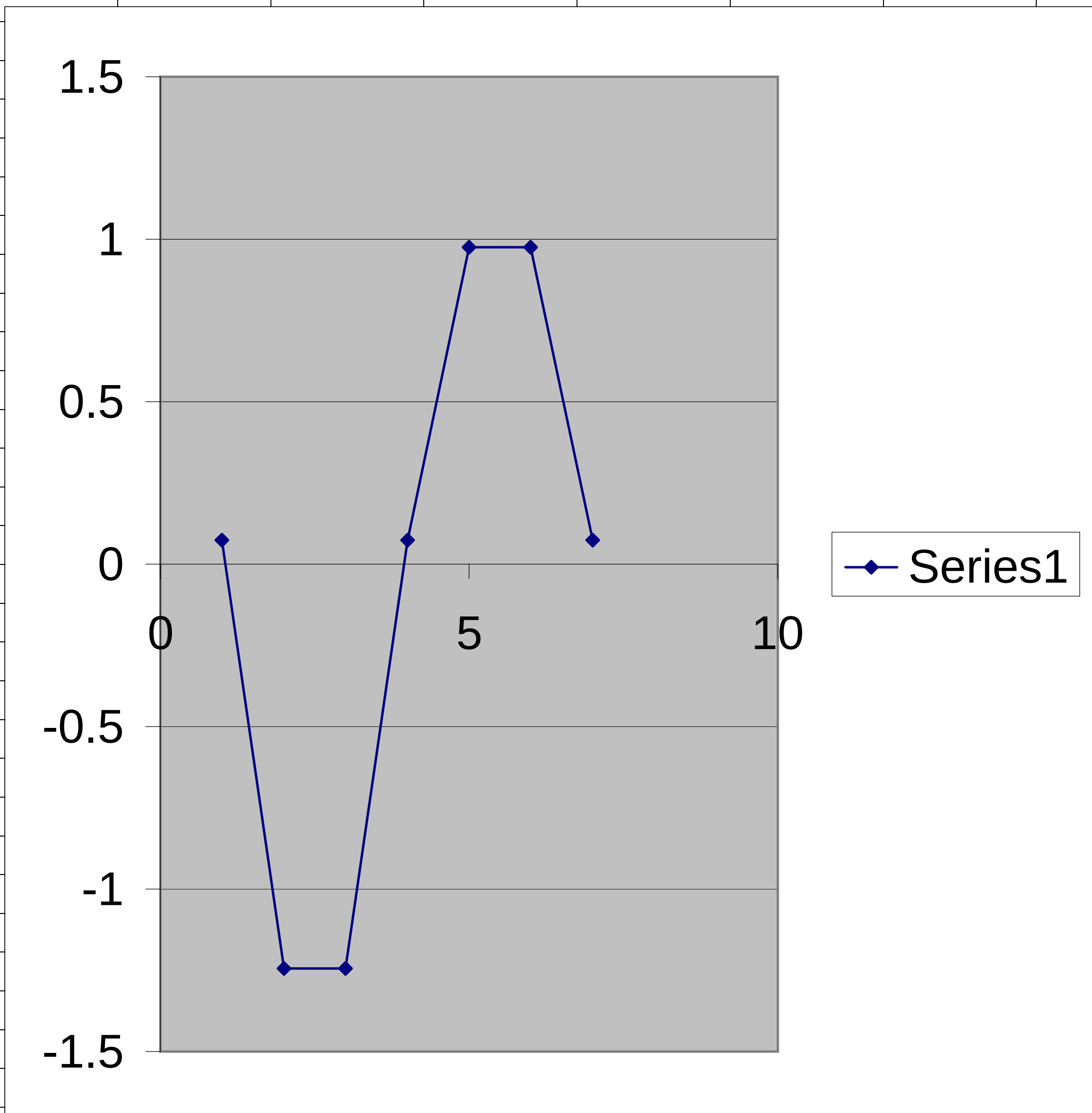
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0.5
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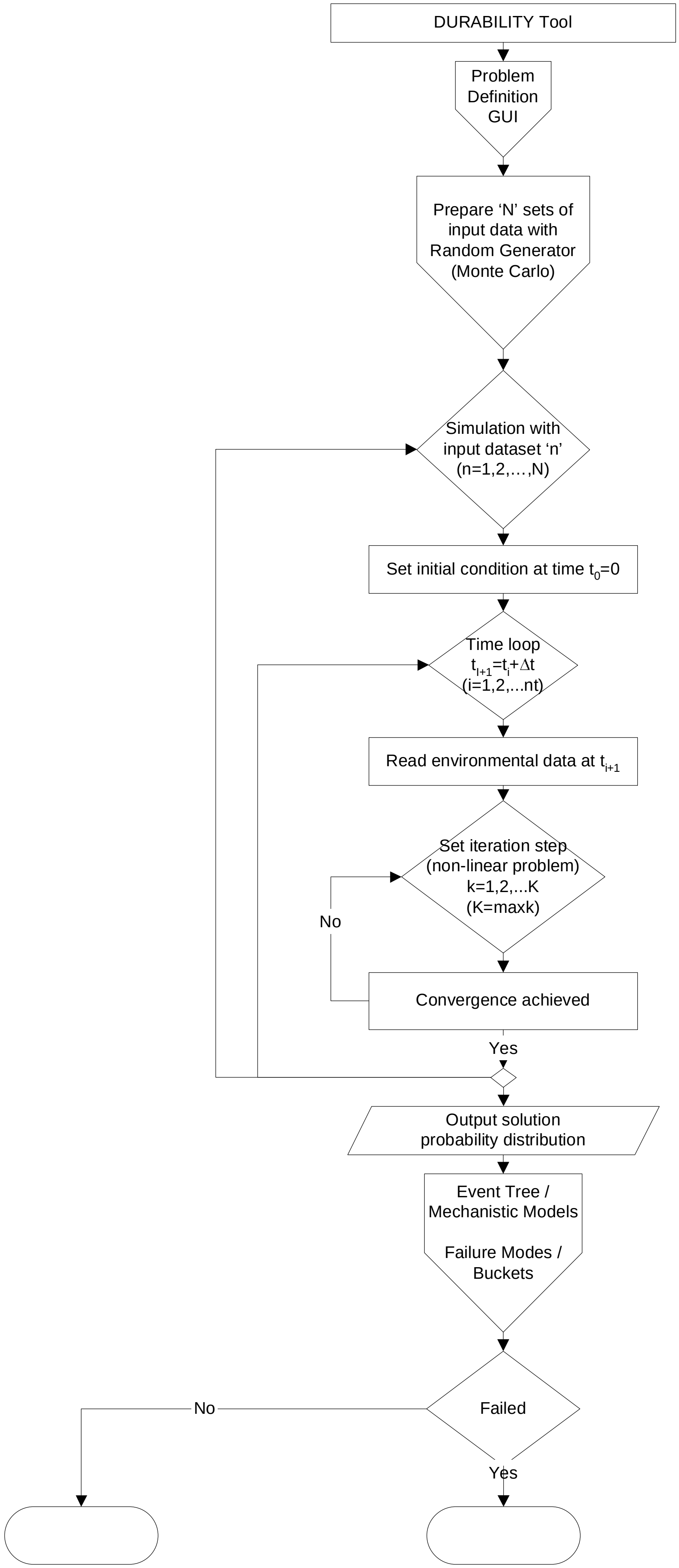
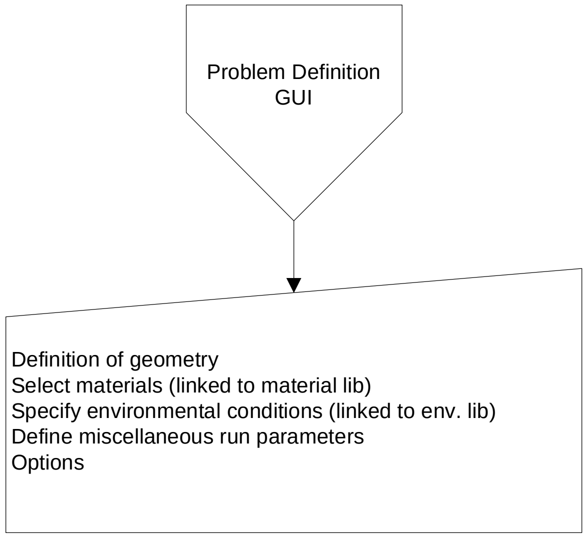
-0.5
-1
-1.5
0
5
10
Series1

Appendix 7

Durability Flow Chart


DURABILITY Tool
Problem Definition GUI
Prepare 'N' sets of input data with Random Generator (Monte Carlo)
Simulation with input dataset 'n' (n=1,2,…,N)
Set initial condition at time t_0=0
Time loop $t_{i+1}=t_i+\Delta t$ (i=1,2,...nt)
Read environmental data at t_{i+1}
Set iteration step (non-linear problem) k=1,2,...K (K=maxk)
No
Convergence achieved
Yes
Output solution probability distribution
Event Tree / Mechanistic Models
Failure Modes / Buckets
Failed
No
Yes



Definition of Geometry:

- pre-prepared geometries
  - dimensions
- drawing tool (THERM?)

Material Properties:

- selection for pre-prepared geometries
- selection for drawing tool

Material Library:

- List of predefined materials
- Edit library
- Input new data in a library
- definition of properties and tolerances
-

Environmental Conditions:

- select env. cond. set
- select random generator?

Library of Environmental Conditions:

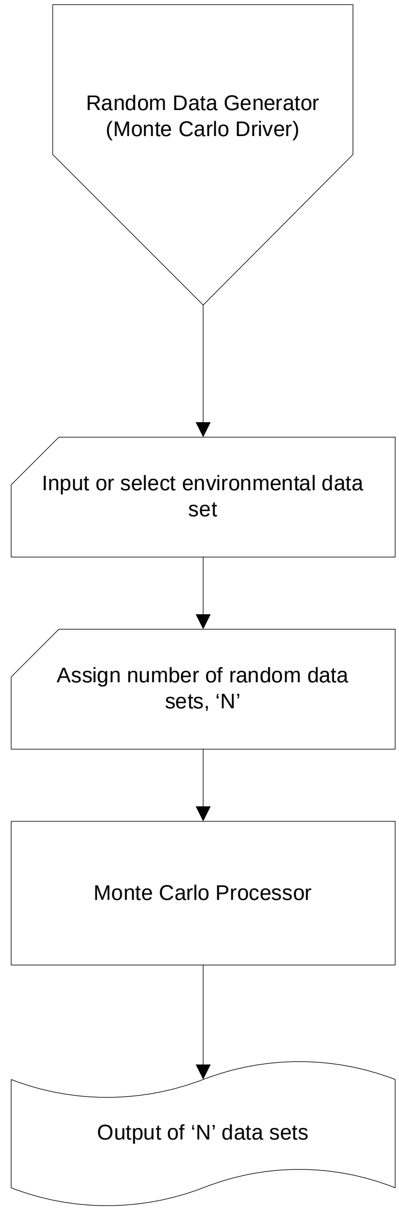
- List of predefined env. cond.
- Edit library
- Input new data into library
- Access to actual weather data
- List of random generators?

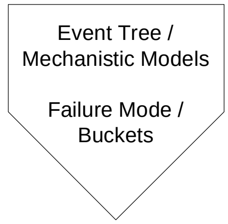
Miscellaneous Run Parameters:

- Failure criteria (is this really input parameter??)
- Define number of simulation runs
- Define simulation period
- Define numerical parameters (select from list?)

Options:

- Define list of program options
- Determine which options will be tied to program and which will be tied to file saved
- Define defaults
- Define program preferences


Random Data Generator
(Monte Carlo Driver)
Input or select environmental data set
Assign number of random data sets, ‘N’
Monte Carlo Processor
Output of ‘N’ data sets


Event Tree /
Mechanistic Models
Failure Mode /
Buckets

Appendix 8

Carli, Inc. Final Report

Carli, Inc.
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Amherst, MA 01002
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home@fenestration.com
http://www.fenestration.com

Final Report:

Oversight of the IGU Durability Model and Standards Development, and Project Coordination Services

Submitted to:

Aspen Research

June 14, 2005

BACKGROUND

Phase I of the IGU durability knowledge base project had been expanded to include computer tool development that can be used by fenestration industry to predict durability of IGU products in an user friendly and consistent manner. The development of this tool is a critical component of the project, because it introduces, for the first time, an industry standard for the prediction of service lifetime and durability. This is the kind of tool that has long been sought by the industry and professionals in fenestration related field.

Carli, Inc. has a history of computer tools development that provide user friendly and practical application for industry professionals. While the company has worked primarily in the field of thermal and energy performance of fenestration systems and whole buildings, nevertheless, its experience in the development of standardized tools brought valuable addition to the project. The outcome of this project, with the help of Carli, Inc. is expected to result in the development of the first tool of its kind in the service life prediction and durability field. It is also expected that the experience and results from this project that deals primarily with IG durability, will be expanded to the entire field of fenestration products, including frame components.

DELIVERABLES

Deliverables for this project from Carli, Inc. has been completed in phases and submitted timely. This final report includes all of the major published material and progress reports submitted over the course of the project. Some important highlights:

- Coordination of computer tool development resulted in following compatibilities:
    - W optical and thermal calculations
    - IGDB compatible
    - Standard weather data
    - Database foundation
    - Xml interface
    - Fortran 90 source code
    - Seamless future updates
- Sealsim fulfils the promise of being the first usable durability tool for fenestration products
- GUI provides industry standard interface that can be easily expanded
- Weather data modified to include Monte Carlo parameters for random variations and provision for extending data set beyond one year provided
- New method of real-time simulation developed during the project
- Devised novel approach of combining real-time simulations with FMEA and proposed as a future path

- Technical paper written on the novel approach
- Proposed novel approach of simulating accelerated testing conditions and developing durability prediction from that. New standard to be developed on this premise
- NFRC, IGMA and AAMA fully both-in into the approach and consortium of manufacturers and government formed to continue the project
- Developed proposal and submitted to DOE for continued funding

The cumulative project reports and progress reports follow:

Short Technical Progress Report on the Oversight of the IGU Durability Project:

Date: ***June 2, 2003***

Period Covered: ***March 1 to May 1, 2003***

- **Oversight of the model development**
  - *Collaborate with Aspen and learn about their mechanistic model.*

    The literature review had been conducted and relevant papers and reports were reviewed. Several references were obtained from Aspen, including the Phase 1 Report. Basic understanding of the mechanistic model and its relationship to the physical model has been achieved. The kick off meeting at Aspen was attended and better understanding of the overall project has been achieved.
  - *Collaborate with TNO and learn about their physical models and coding capability.*

    Physical modeling capability of TNO has been assessed through their presentations and discussions during the meetings at Aspen and TNO in February and March. Further discussions and interactions with TNO have resulted in better understanding of their capability to develop intended tool.
  - *Learn about interaction between mechanistic and physical models and guide the development of integrated model. Weigh complexity/ resolution vs. optimal resolution from the standpoint of data collection and input into computer program.*

    During the meetings and subsequent follow-ups, the interaction between mechanistic models and physical models has been understood quite well. This has resulted in fairly clear picture of the overall structure of the intended computer program.

    Development of the more specific flow chart of the program, showing how will mechanistic models interact with physical models is planned as the next step.
  - *Closely coordinate GUI development and define inputs/outputs and interaction between different objects.*

    Not started yet.
  - *Define the role of existing DOE tools and ways to enhance them and interface with TNO code. Define additional/modified I/O, GUI, algorithms.*

    The proposed tools for physical modeling (i.e., ESTSC tools) were reviewed and agreed upon. Caution was communicated regarding potential slowdown of the program development due to the switch to ESTSC tools as opposed to TNO based tools.

    It is planned to work closely with TNO in the process of adopting new tools and reviewing the source code.

- *Provide database engine foundation and interaction within the intended new tool.*

  Not started yet

- *Assure buy-in of new methodology/tool (NFRC, ISO, LBL, IEA, other).*

  Discussions with Bipin Shah at NFRC, Dariush Arasteh at LBNL, Bill Lingnell, the convenor of the ISO WG has been carried out and they support the intended goal of the project. Dariush has agreed to help integrate existing fenestration tools (i.e., THERM, WINDOW) into the future tool. Discussions was held with several participants of IEA Task 27 meeting in Lisbon, Portugal.

Overall Coordination

- *Initiate, coordinate and communicate peer review process.*
  This is an ongoing activity and will be stepped up in the next stages of the project as the computer tool development progresses.

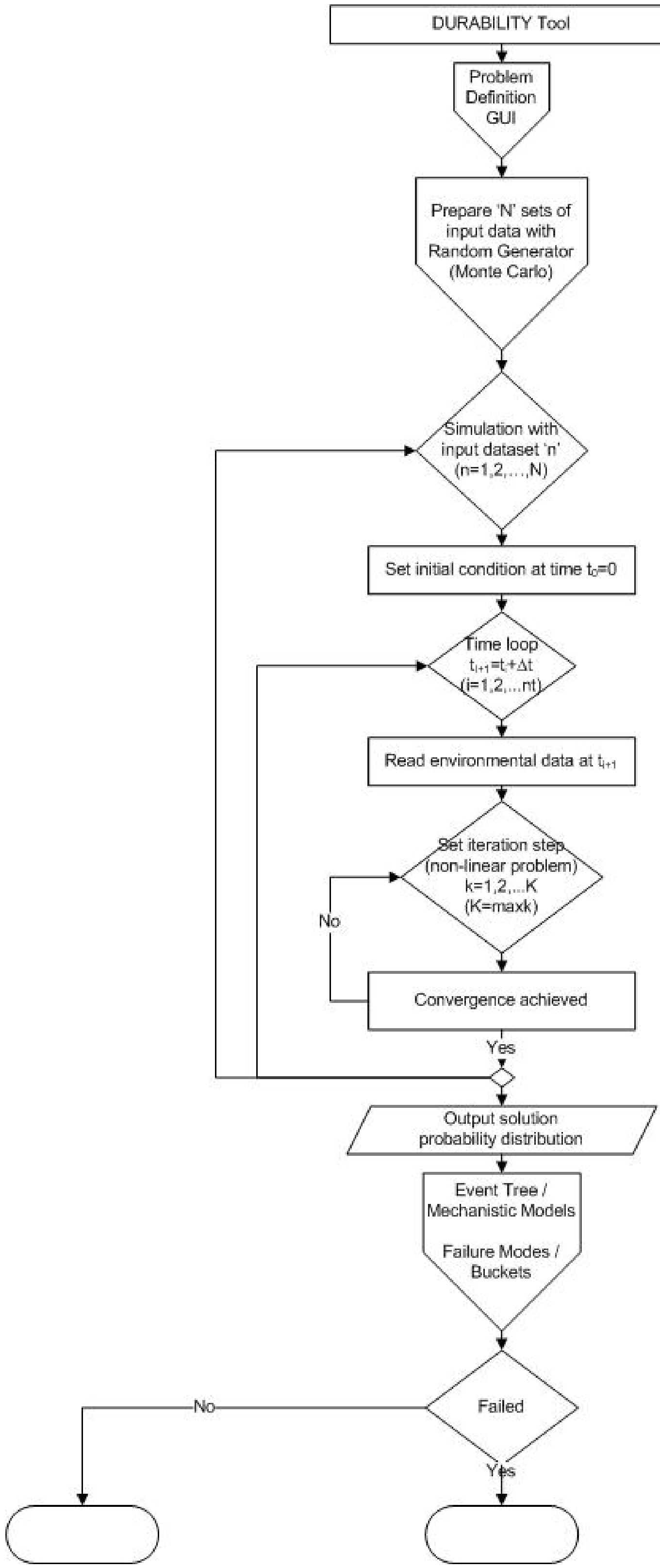
Comments and Remarks on the Insulated Glass Knowledge Base Project:

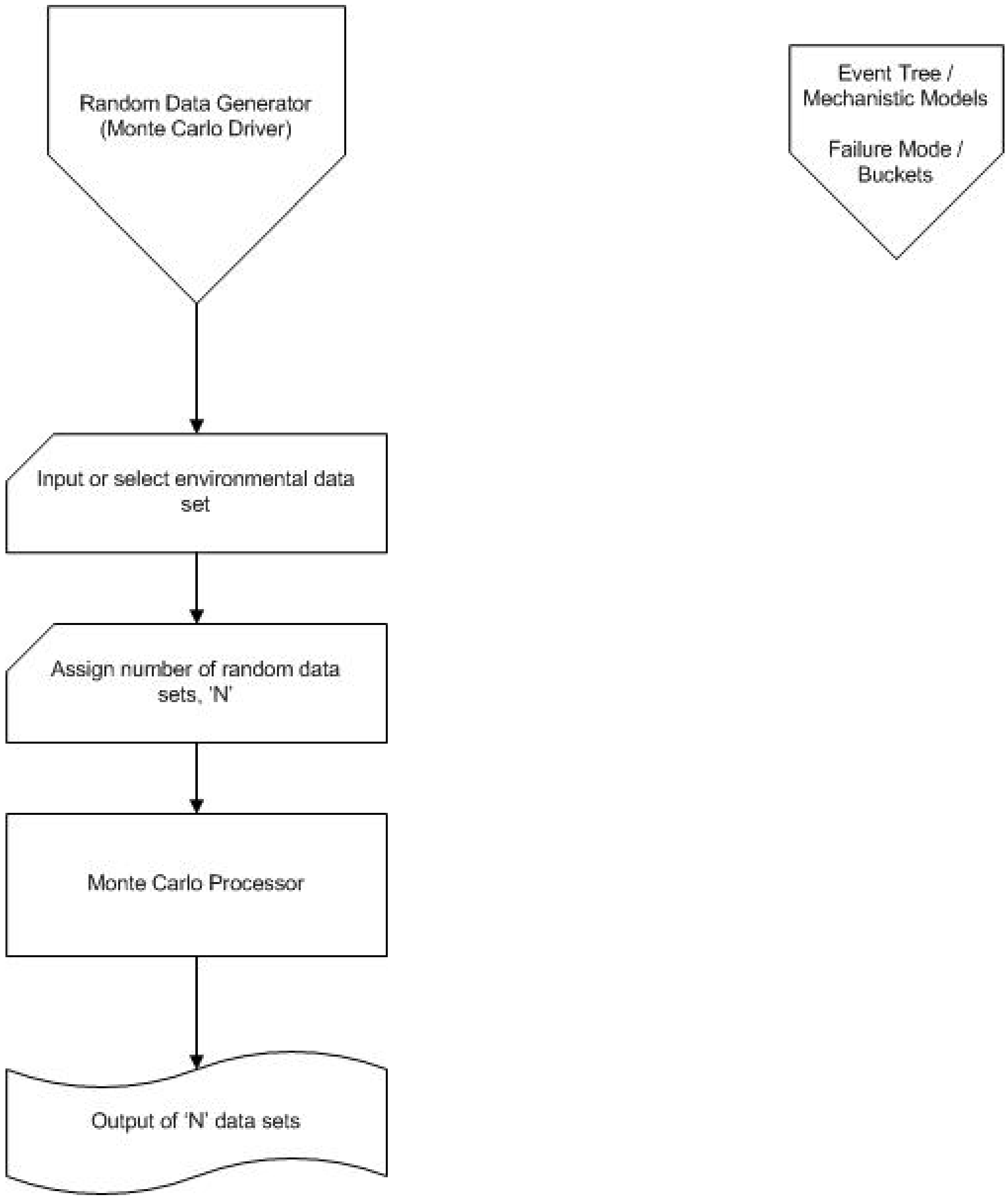
By: Charlie Curcija

Date: 7/22/03

1. It is important to have good Random Generator. What is the choice at this point?
2. Who is going to provide tolerances for material properties and their correlation to random distribution (is Monte-Carlo generator going to provide this distribution?)
3. Mutual dependency of failure modes in the event tree needs to be defined. Partial failure would need to be input into the next time step.
4. How are failure modes (buckets) related to the distribution of physical variables (i.e., stress/strain, temperature, moisture migration, etc.)? We need clearly defined mechanistic models for this (i.e., need to be programmed).
5. "optimization" of the algorithm will probably become Issue, because number of equations to be solved could be enormous.
6. GUI outline/proposal
7. Are we having change of properties over time? Are we defining functional dependency of properties on other variables (i.e., function of temperature, humidity, etc., while these same properties are being solved for – i.e., increased non-linearity of the problem.
8. In addition to flow chart, database structure will need to be defined.
9. Temperature model is set up somewhat differently than in ISO15099 and WINDOW.
10. In write-ups on physical models there is no discussion of numerical solution
11. Revised flow charts attached
    a. Event tree and failure mode included into the algorithm
    b. Detailed flow diagram of event tree needed (Aspen?). This needs to be in a programmable format (i.e., specific set of algorithms)
    c. Outline of GUI and dependencies provided
    d. Failure modes (buckets) and their relationship to physical models (mechanistic models?) need to be defined to sufficient specificity to be programmable (i.e., specific set of algorithms)

Flow Chart of the Proposed Durability Tool




Random Data Generator
(Monte Carlo Driver)
Event Tree /
Mechanistic Models
Failure Mode /
Buckets
Input or select environmental data set
Assign number of random data sets, 'N'
Monte Carlo Processor
Output of 'N' data sets

Discussion and possible directions for preparing translator for 2-D and 3-D programs into 1-D and 1½ D.

***Date:* 1/13/04**

Discussion and possible directions for preparing translator for 2-D and 3-D programs into 1-D and 1½ D.

Current work on 1 D and 1½ D heat transfer and mass transfer models involves mostly 1-D physical model results (center of glass for thermal and 1-D mass transfer through homogenous slabs, corrected by area weighting – that is face area for mass transfer through spacer assembly). This approach has been deemed appropriate for this phase of project due to a large number of possible configurations and prohibitively expensive running time if full 2-D and 3-D models were incorporated. It is also a sensible approach for problems for which almost nothing has existed before and where there are so many possible interactions and unresolved consequences. This paper will describe; a) some immediate suggestions for improvements in this approach, which can easily be implemented in this stage of the project, and b) recommendations and directions for future work, which can be either incorporated into the new proposal to DOE or can serve as a general guideline for future work.

Possible Improvements to current models:

In the area of **thermal modeling**, 1-D heat transfer prediction through center of glass is reasonable estimate of average temperature that exist on each side of the glazing. This prediction can be successfully used for predicting bulk gas properties in the cavity and are somewhat less reliable for predicting temperature of the sealant and spacer.

This prediction could be improved by considering effective conductivity of spacer assembly (see procedure in Appendix A) and correlating this value to center of glass temperature distribution in developing simple correlation for sealant and spacer assembly temperatures. Absence or presence of Solar radiation on the whole exterior surface or certain sections of the IGU can also be included in a correlation for predicting temperature distribution in a sealant.

In the area of **mass diffusion** modeling, effects of interface between sealant and spacer and measure of their adhesion can be also correlated to provide correction factors to simple area weighting of surface areas in predicting mass transfer through the spacer assembly.

In the area of **stress and strain** modeling it is not yet clear how the 1½ D model works, so further comments will be left for after the model has been disseminated.

Future Directions for Translating 2-D and 3-D models to 1½ D models

The translation from multi-dimensional models into their reduced form (i.e. 2-D into 1½ D and 3-D into or 2½ D) can be accomplished using two basic approaches; 1) utilization of numerical methods (brute force approach) to solve full set of governing equations without simplifications; and 2) introduction of simplifying assumptions into the governing equations in order to accomplish analytical solution in a closed form. Combination of the two approaches may also be appropriate. Depending on the approach, the problem can either be directly incorporated into the durability tool (more appropriate for simplified analytical models) or the results of physical models are mapped (translated) into the analytical model built-in into the durability tool (appropriate for numerical solution). In its extreme cases, full multi-dimensional numerical models could be incorporated into the durability tool, and while this option would provide almost absolute accuracy, the hurdles to implementation of such method are so huge that it will take many years for this approach to be viable. However, implementation of numerical simulations in some limited form prepares the model for future full implementation, where translator is simply replaced by the full numerical model.

Analytical Approach

A general method of 2D to 1D translation of governing equations is obtained by integration in one dimension of the 2D model. If the modeled system is homogeneous in the integrated dimension (i.e. all of the slabs are the same) the translation comes down to simple area weighting. An example of such system is the IGU, incorporating TPS spacer. In this case area weighting will give exact translation for diffusion equation. In the case of non-homogeneous system (example: Box-spacer system) simple area weighting translation may be more or less oversimplification. In the case of a box-spacer system, the area through which the vapor enters the interior of the unit (the area between the box spacer and the glass panes) is much smaller (10-20%) than the total area of the seal. Translation by weighting with the total seal area will clearly overestimate the effects of diffusion in this case (??). Weighting by the area between the box spacer and the glass panes will, however, underestimate the diffusion effects. The vapor diffuses in the region under the Box-spacer too. In this case the diffusion paths through slabs are not the same, and more importantly, they are not parallel.

The disadvantage of this approach is that there may be some oversimplifying assumptions and sometimes we may not be able to determine if they are oversimplifying or not. The advantage of course is very fast calculation time, which sometimes may be critical. It may be that final choice of models is a mixture of different approaches, so this alternative is presented here.

Numerical Approach:

This approach consists of reading results from numerical simulations of 2-D and 3-D models and then interpreting those results and incorporating them into 1-D models in order to create 1½ D models. The most practical way of incorporating numerical approach is to use existing 2-D numerical tools, which incorporate some limited 3-D effects (i.e., THERM, WINDOW, etc.), solve physical models for number of boundary conditions and develop interface for those tools to interpret these results and prepare input data for use in the durability tool. For example, THERM program could be run for variety of input and boundary conditions and data at strategic locations can be extracted to construct input data for the thermal stress model. These strategic points could be center of glass, beginning and end of spacer assembly interface with glass, interface of

IGU and frame, average temperature of frame components, etc. Another example, involving diffusion would be taking sampling points in the middle of the sealant, diffusion distribution at the interface with glass and sealant, as well as sealant and spacer, which can be used together to construct 1-D data for input into the durability tool. In this scenario, durability tool is largely left intact, with its existing 1-D treatment of physical phenomena and with the improved estimation of 2-D effects for the better definition of 1½ D models.

Alternative path would be to incorporate full 2-D and 2½ D physical models into the durability tool scheme, which would provide less simplifying assumptions, but would require significantly more execution time, being possibly prohibitively expensive in terms of running time for several years to come. This approach, however, is the right way to go into the future when the expense of computer running time and resources will not be playing significant role. Some sensible mix of these two approaches seems to be the most effective path.

Appendix A: The calculation of k_{eff} of the spacer assembly was done according to the following procedure:

Overall U–factor of individual spacer assembly, shown on Figure A-1, was calculated using THERM 5, using the following boundary conditions on the side (i.e., left and right) boundaries:

Exterior surface

NFRC Exterior combined (t = - 0.4 ºF, h_o = 5.283 Btu/h*ft^2*F)

Interior surface

NFRC Default Interior combined (t = 69.8 ºF, h_i = 1.408 Btu/h*ft^2*F)

- From the electrical analogy of heat transfer mechanism:

$$R_{tot} = \frac{1}{U} = \frac{1}{h_o} + \frac{L}{k_{eff}} + \frac{1}{h_i}$$

(A1)

k_{eff} can be determined as:

$$k_{eff} = \frac{L}{R_{tot} - \frac{1}{h_o} - \frac{1}{h_i}}$$

(A2)

where :

- L = spacer width,
- R_{tot} = overall thermal resistance of considered spacer,
- h_o = outdoor heat transfer coefficient,
- h_i = indoor heat transfer coefficient.

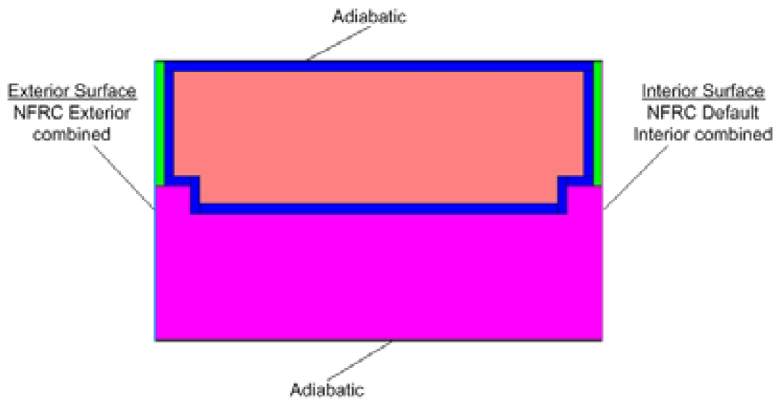


Figure A-1. Boundary Conditions and Spacer Configuration Used for k_{eff} Calculation

Appendix B: Example of Analytical Solution of Diffusion Equation With Point Source

In the following derivation an extreme case of non-parallel slabs is solved. The diffusion through the slabs in the following example radiate from a single point. The final result however is surprisingly simple.

Diffusion equation in 2D and 1D

3-D case

Diffusion equation in general 3D case:

$$\frac{\partial \rho}{\partial t} = D(\frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial y^2} + \frac{\partial^2 \rho}{\partial z^2})$$

where ρ is mass density and D is the diffusion constant. A special case is the steady state (generally established after a certain characteristic relaxation time):

$$0 = D(\frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial y^2} + \frac{\partial^2 \rho}{\partial z^2})$$

2-D case

In 2D the equation becomes:

$$0 = D(\frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial y^2})$$

The solution of the equation depends on the boundary conditions. In the case of single point mass source, the boundary condition can be taken as:

$$\rho(x=0, y=-d) = \rho_0$$

and

$$\rho(x, y=0) = 0 \, .$$

The solution in this case is:

$$\rho(x,y) = \rho_0 (\ln \sqrt{x^2 + (d-y)^2} - \ln \sqrt{x^2 + (d+y)^2})$$

It is clear that:

$$\rho(x, y=0) = 0$$

There is a problem with the point x=0 y=-d but it can be solved by assuming boundary conditions on a cylinder instead of a point.

1D case

In 1D case the solution under the given boundary conditions is:

$$\rho(y) = -\rho_0 \frac{y}{d}$$

2D to 1D translation

In order to translate the 2D to 1D solution we can perform integration over the x coordinate:

$$\rho(y) = \int_{-\infty}^{+\infty} \rho(x,y)dx$$

Knowing that:

$$\int \ln(x^2 + a^2)dx = -2x + 2a \cdot arctg(\frac{x}{a}) + x\ln(x^2 + a^2)$$

we get:

$$\int_{-\infty}^{+\infty} dx(\ln\sqrt{x^2+(d-y)^2} - \ln\sqrt{x^2+(d+y)^2}) = -x + x + (d-y)arctg(\frac{x}{d-y}) - (d+y)arctg(\frac{x}{d+y})$$
$$+\frac{x}{2}(\ln(x^2+(d-y)^2) - \ln(x^2+(d+y)^2))\Big|_{-\infty}^{+\infty}$$

since the first two and the last two factors cancel out and $arctg(\pm\infty) = \pm\frac{\pi}{2}$ we get:

$$\int_{-\infty}^{+\infty} dx(\ln\sqrt{x^2+(d-y)^2} - \ln\sqrt{x^2+(d+y)^2}) = -2y\pi$$

The fact that we can obtain the form of the stationary solution of 1D diffusion equation (linear function) just by integrating the stationary solution of the 2D diffusion equation for the given boundary conditions suggests that the translation of the problem from 2D to 1D in a non-homogeneous geometry can be as simple as integrating over one of the coordinates. The solution may be as simple as the following relation between the outside density for the 1D and 2D case:

$$\rho_0^{1D} = (2\pi \cdot d)\rho_0^{2D}$$

Clearly, a case of more complex geometry will result in a different factor. It is important to note, however, that for each geometry we can define a constant factor for translation, no matter how complex the geometry is. This factor can be obtained either by analytical or numerical integration of the 2D diffusion equation.

Future Directions in Improving the Prediction of Failure Modes

***Date:* 2/5/04**

In the Insulated Glass Durability project, two general concepts of systems simulations were considered so far:

1. Simulation model based on event tree diagrams

2. Real-time calculation procedures

1. Event tree diagrams

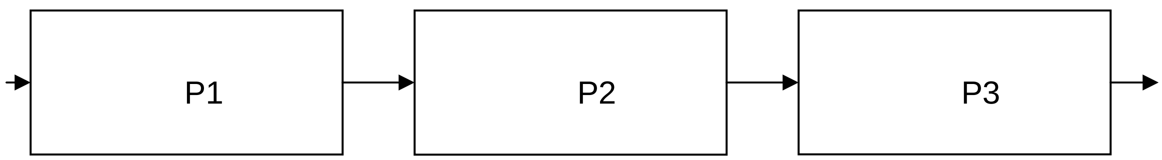
The event tree diagrams method was outlined in the Phase I Final Report. In the event tree approach the problem is divided into several independent failure modes connected through the mechanistic models. Examples of failure modes are: sealant adhesive failure, desiccant saturation etc. The failure modes of the IGU systems were identified and defined by the **F**ailure **M**odes and **E**ffects **A**nalysis (FMEA) as explained in sections 3 and 4 of the Phase I Final Report.

By considering different failure modes, the system is divided into simplistic units. Each unit can be modeled by a physical model. The environmental stress is given by a stochastic model based on a climate database. In each failure mode the environmental stress is translated into material stress according to a physical model. On the other hand, the material properties are also given by a statistical model based on a materials properties database. After the solution of the physical model, a probability distribution for failure to occur in a given mode is obtained. The modes of failure are organized into event tree diagrams. Relations of cause and consequence are defined between different modes. These relations form network of connected failure modes. This network of modes is the event tree diagram. In the Phase I Final Report event tree diagrams were outlined for each class of IGU. An example of an event tree diagram is given in Appendix I.

The objective of event tree simulations is to calculate the probability of failure of the entire system. Also, other stochastic characteristics can be calculated, such as mean first passage time (the average life-time of the system), etc (Singh and Billington, 1977). If the event tree is simple and linear as in Fig. 1 , the probability for failure can be easily calculated (P=P1*P2*P3). Complex networks (see Fig. 2) however cannot be solved exactly (i.e., closed form solution). The only way to calculate the probability of failure for complex systems is to perform Monte Carlo simulations.

In a typical Monte Carlo simulation a single path of events will occur. At each failure mode block a random event will occur according to a probability distribution. Depending on the outcome at a given block, the flow of events can take several directions to several following failure mode blocks. For each Monte Carlo run only one path will be taken. After a large number of repeated Monte Carlo runs (for the same initial conditions) a set of paths will be sampled. Given the set of paths, it is easy to determine the most probable path of events, mean first passage time, etc. It is clear that in this case the entire system is not simulated in real time. The average lifetime is determined from the probability of failure.

The differential equations of the physical models are solved in order to obtain the probability distribution for failure for each mode. This way, simultaneous solving of the differential equations is avoided. The system is separated into simple units connected into a complex network of events.



$$P = P1 \times P2 \times P3$$

Figure 1 A simple system that can be solved exactly.

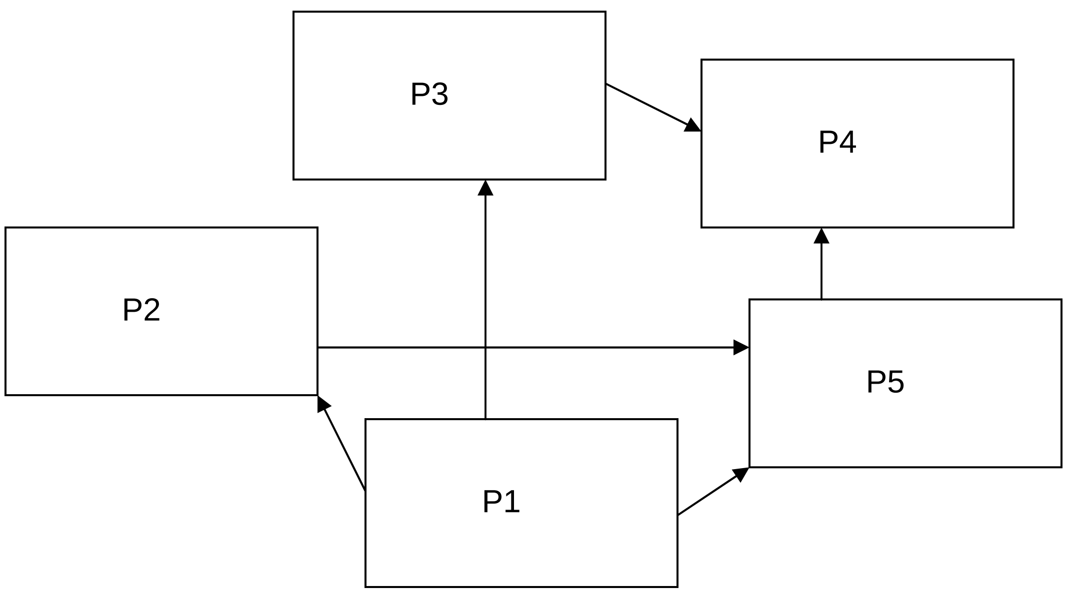


Figure 2 A complex system that can not be solved exactly.

This method has advantages of being less resource consuming, and therefore faster. It also has elegant structure and simple appearance. The disadvantage of this methodology is that interactions between different models and failure modes need to be precisely defined and failure paths clearly identified. This is not trivial task and for complex system like a window, it would require significant research effort to develop these relationships and interactions. Also, precise event tree would need to be developed so that coding of the simulation tool can be accomplished. This effort was not conducted as a part of Phase I project, and instead concept and outline of methodology was developed.

2. Real-time calculations

In this approach the complexity of the system is captured by a model involving simultaneous solving of many differential equations or sets of differential equations, acting simultaneously on the system. (i.e., one physical phenomena that may cause failure and has associated failure mode will affect or will be affected by another physical phenomena to a larger or smaller degree, depending on their coupling). Each equation is given by a physical model (transport of heat, transport of mass, etc.) and their coupling is established through the independent variables present in more than one set of equations (e.g., temperature, pressure, etc.) The system of differential equations is solved in real time. This is a realistic simulation of the actual physical behavior of the system in real time. After a certain time, the system may fail (according to a definition of failure) and the simulation will be stopped. This simulation procedure will be repeated for many, at random chosen initial conditions and material properties, both given by stochastic models (i.e., initial conditions and material properties are not fixed and they will vary based on the prescribed set of mean values and possible departures from those mean values – e.g., material tolerances for material properties). After many simulations are performed for a sufficiently long time period (e.g., 30, or 50 years) a set of times to failure will be generated. In these simulations it is necessary to consider long enough time to be able to capture failure (e.g., if the unit is going to fail after 22 years, running simulation for 20 years, or for 10 years will not going to tell us when the unit is going to fail, therefore not giving us enough information to conclude about the durability and lifetime of the unit). Based on all of times to failure that we calculate this way, mean lifetime of the product could be obtained.

Solving simultaneously a full set of differential equations in 2-D or 3-D for a system as complex as an IG unit can be difficult to perform and it is highly demanding in terms of computer resources (it should be noted that the simultaneous set of equations would need to be solved for N sets of random material properties that are determined from the mean and tolerances set through input data and some statistical distribution of these properties within those tolerances and performed for a sufficiently long period of time, which would enable determination of time to failure). In order to reduce running time and overall complexity, which is likely to be prohibitively expensive at this point in time, a complex system case is described by a simplified model (e.g. 1-D and 1-½D model instead of full 2-D or 3-D simulation). The complexity of the system is therefore reduced and run times for the simulation will likely now be acceptable.

The lifetime of the system is obtained after averaging over a large enough number of simulation runs. Each simulation run is started with different random initial conditions. The run lasts until the system fails. The time until failure (life-time) is recorded for each run. A measure of durability in this case can be obtained by taking the average of the recorded life-times.

The advantage of real-time simulations is in the fact that coupling and interactions between different physical models falls out naturally from the interactions between equations describing different physical models. No special relationships need to be defined. The disadvantage of real-time simulations approach is in the need to solve simultaneous sets of equations for the entire system and for large number of initial conditions each time. This is resource very intensive and not very efficient.

In this project, real-time simulations were selected as a method of choice because the amount of work and effort needed to be spent in defining relationships between each mode of failure in event tree and development of specific and complete event tree far exceeds allocated budget and available resources. It is, however, feasible to extend existing real-time approach and to develop event-tree methodology in the future continuations of this project, which would also allow for the utilization of more sophisticated physical models as well (i.e., use of 2-D numerical tools instead of 1½-D models.)

3. Future Integration of the Two Methods

Both methods described above can deliver same measure of a product durability: average life-time of a system. There is a crucial difference, though, in the method of obtaining the average life-time. In the **event tree diagram**, the time measure is obtained from a probabilistic method. The system is not simulated in real time. Instead each of the failure modes is solved and a probability of failure for each mode is defined. The system is modeled by a network of interconnected failure modes that can be solved by Monte Carlo sampling. The life-time of the system is derived from the calculated probability of failure of the system.

A way to integrate these two methods is to perform real-time simulations for each of the failure modes. The interaction between the individual failure modes would need to be defined externally through the use of mechanistic models, which would be based on both measurement and simulation of the complete systems. These real-time simulations will provide the probability of failure in each mode. After the real-time simulations are finished for all failure modes, those failure modes can be organized into an event tree diagram, which can be solved by a Monte Carlo method. This approach was outlined in a flow chart presented by Charlie Curcija (document: "Durability-Flow_Chart.pdf" from July 2003).

It is clear that in each block of the event tree diagram a probability distribution for failure has to be defined. This probability distribution is obtained by multiplication of the probability distribution of the environmental stress and the probability distribution of the maximum allowed material stress. The probability distribution of the environmental stress will be obtained by a time series (real time) simulation of the system. This real time simulation will incorporate all of the elements of the system (in the way currently considered as a simulation of the entire system).

The material properties in this stage however will be fixed and no failure will be considered. This way we can construct a model of translation of the environmental conditions (given by a time series of a typical climate year) into stress probability distribution. This real time simulation can be done by a manufacturer, or some other independent simulator. The advantage of this approach is that this real time simulation needs to be done only once. The translation function would be part of the final program. The probability distribution of the maximum allowable stress will also be obtained by the manufacturer of the material, either by a singe set of simulations or determined by measurements. It seems feasible for a manufacturer to supply, for example, the probability of sealant cohesive failure for several IGU classes at different climate conditions.

The advantage of the methodology described above is in the separation of the two methods of simulations:

- The computationally expensive real time simulations are performed either by the authors of the program or a manufacturer of an IGU component (material). These real-time simulations are performed only once and the resulting probability distributions are incorporated into the failure modes of the event tree diagram.
- The relatively computationally inexpensive Monte Carlo simulations of the event tree diagram of the entire system are performed by the end user of the program. This way the user will have better flexibility in designing the system, comparing the durability of two or more designs and deciding to use an optimal IGU geometry and design.

In is important to notice that the real time simulations done by the manufacturers will concentrate on a single aspect/component of the system. It is important therefore that the real time simulations tools are designed with this fact in mind. The manufacturer should be able to exclude the possibility of failure of all except the targeted component of the system. The real time simulation therefore should have the option of switching on and off different failure criteria. Also, the real time simulation tool should provide a translation function from the environmental conditions to materials stress. This should be a case of all failure criteria switched off. The real time simulation should run until sufficient amount of stress data from the systems regular (non-failed) behavior is collected.

- Develop 2-D physical models and provide extension for 2½-D models. Utilizing and leveraging existing 2-D tools and 3-D corrections developed for fenestration performance assessment over the last 20 years (i.e., THERM, SPACER, WINDOW, etc.) as well as the tools under the development (i.e., FENSIZE, UNIFEN, etc.), develop next generation of computer models that would be utilized in the development of the extended durability approach as described in first three points.

Appendix I

An example of an event tree diagram for the TPS IGU (Fig. 3) is given in Fig. 4.

The components of this system are:

- Glazing
- Primary sealant
- Secondary sealant
- Desiccant

Let's assume that the glazing will never fail, but the sealants will have two modes of failure. Both the primary and the secondary sealant could fail due to **cohesive failure** (a crack in the bulk of the sealant) or due to **adhesive failure** (slip and detachment from the glazing). The cohesive failure mode is due to the normal stress exciding the value of tolerance of the material. Similarly, the adhesive failure is due to the tangential stress exciding the value of tolerance of the material.

In our example the system will fail if the desiccant saturates. We can define two ways (failure modes) for the desiccant saturation. First, the desiccant will saturate if the system of primary and secondary sealants fails (the spacer fails). In that case the flow of vapor is free and the rate of saturation (and therefore the probability of failure) will depend only on the material properties of the desiccant. Another possibility is for the desiccant to saturate due to diffusion of water through the sealants. In this case the system fails not due to failure of its components, but due to normal usage (failure due to fatigue). In our example we will consider the saturation of the desiccant after the failure of the sealants immediate compared to saturation due to fatigue. In other words we will consider the system failed once both the primary and the secondary sealants have failed.

In the example given in Fig. 4 we assumed that the secondary seal will fail only if the primary seal has failed. This seems plausible given the fact that the secondary seal is thinner than the primary. Also we assumed that the secondary seal can fail in the adhesive mode after cohesive failure of the primary seal, but cannot fail in the cohesive mode after adhesive failure of the primary seal. In other words we assumed that the attachment of the secondary seal to the glazing is much weaker than the strength of the bulk material. Certainly these assumptions may not be true for a given system. Each real system must be analyzed carefully in order to identify all of the possible failure modes and their relationships. Now, once we defined the event tree diagram, we can solve it in order to calculate the probability of failure compared to the probability for the system to fatigue.

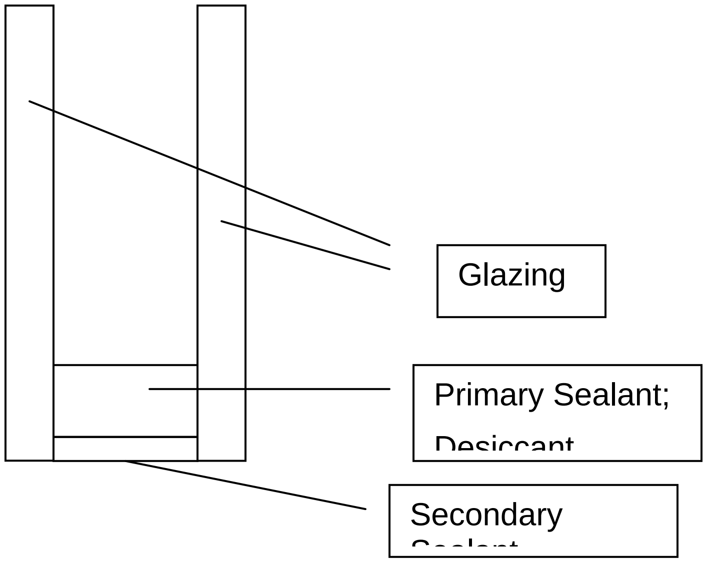


Figure 1. TPS IGU example

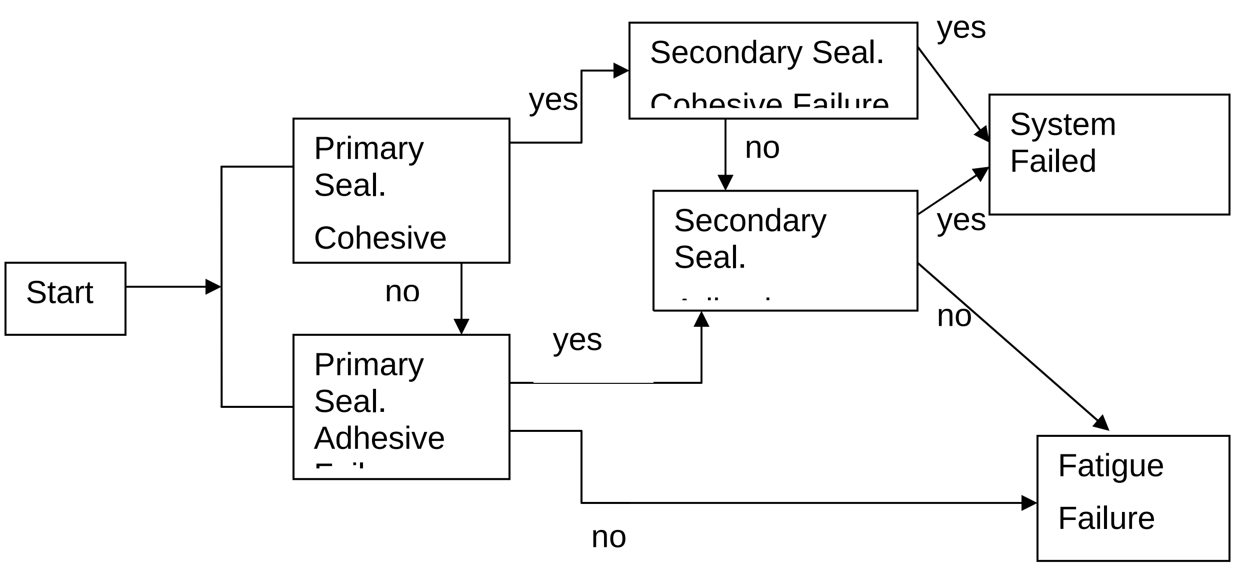


Figure 2. Example of a small portion of event tree diagram for a TPS IGU

Development of a Proposal for the Continuation of Durability Project:

Initiated: 3/5/04
Completed:

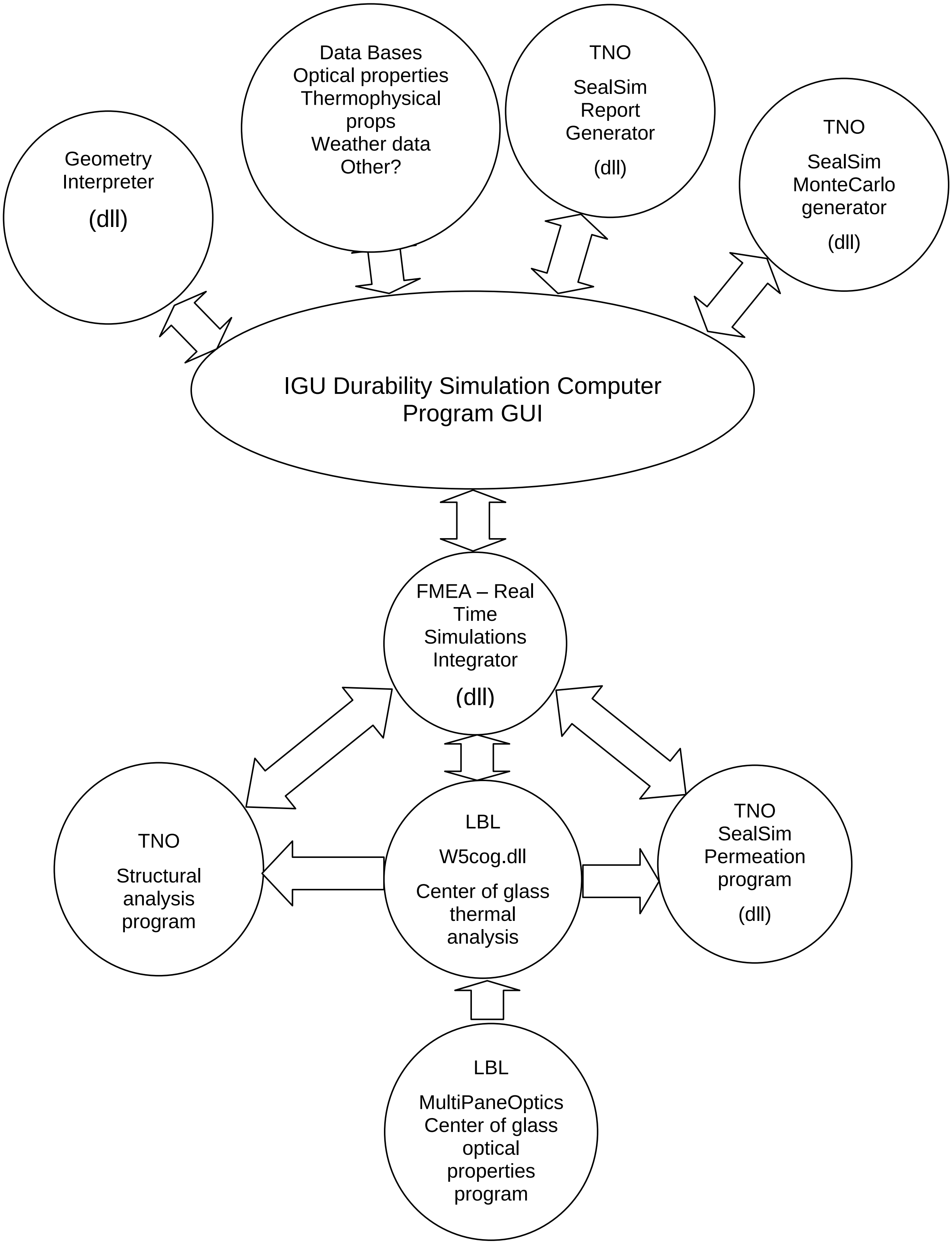
An outline of a proposal for future directions in the IG durability project

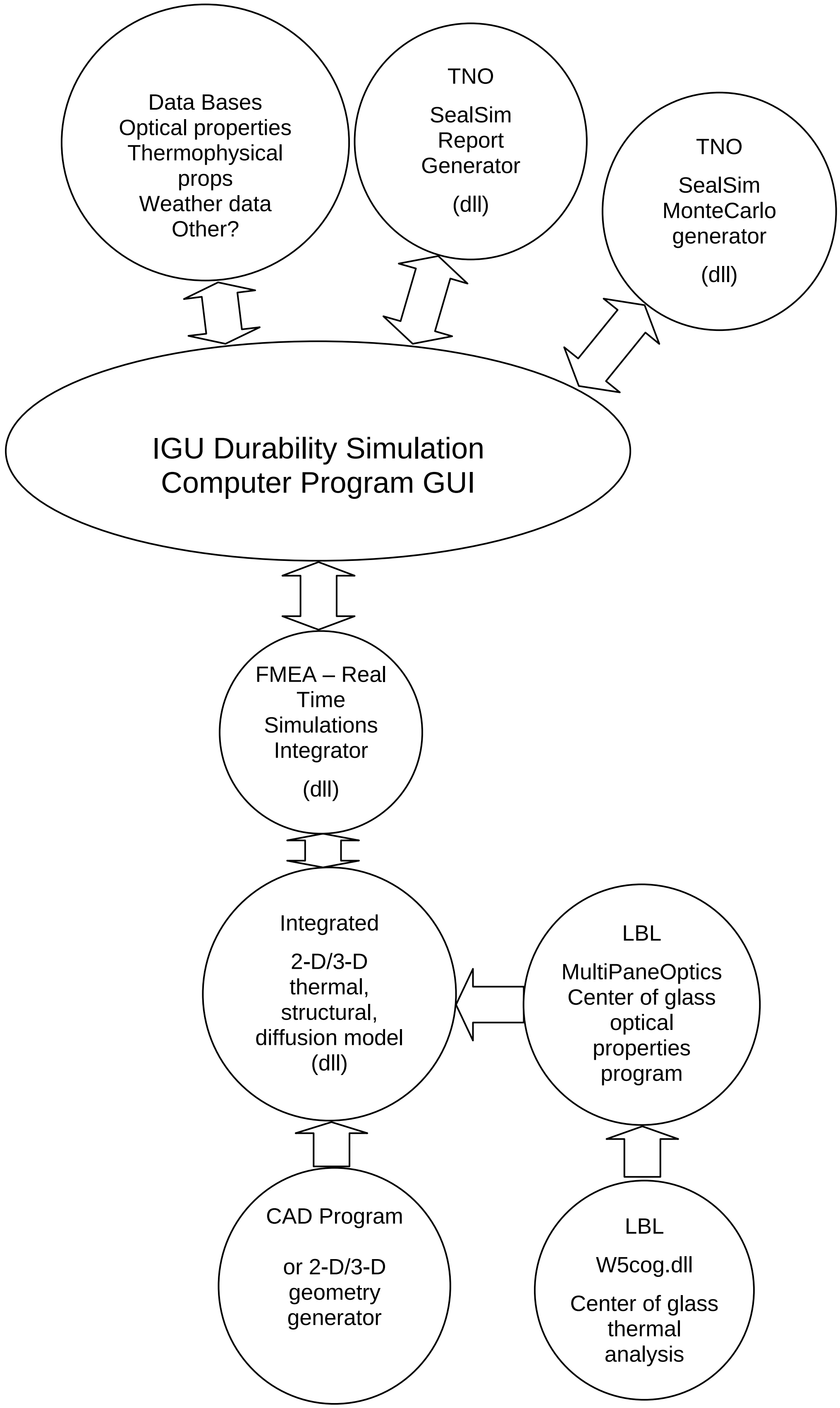
1. Organize the model in independent sub-models. In the FMEA and event-tree approach the emphasis is on isolation and identification of modes of failure. Although the current model is real-time simulation, if organized into relatively independent units, in the future it can be used to simulate independent failure modes. Therefore, the equations of the sub-models must be decoupled.
2. Organize the program in modules each representing a sub-model. As a consequence of 1. the programming paradigm should be object oriented programming with each sub-model being coded as a black box with well defined input and output and absolutely independent internal structure (classes in C++ and/or modules in FORTRAN90). This will not be in conflict with the currently proposed real time simulations of the IG unit (each time step will go through several black boxes). Also, each module must be able to run independently (with some of its variables fixed as parameters).
3. Sub-models must be testable in independent runs. Each sub-model simulation should be compared to a laboratory test. Accelerated testing could be used. It is best if the simulations are compared to standardized tests and the results are presented in a standardized form.
4. Comply with standards. Emphasis on standard tests. This is in close relation to 3. See http://www.igdurability.umn.edu/standards.html
5. Sub-models should be flexible enough to allow new IG designs. Currently only 2 IG designs are supported or are planned to be supported. The sub-models should be organized with a wide range of IG designs in mind. The user should be able to create a new design by combining the sub-models, simulate the durability of his design and decide accordingly on the choice of the IG design to be used or constructed. It is very important to organize the model in a way that a change in design will not require a major modification of the model. Change of design should only require reorganization of sub-models.

Important Elements for the Continuation of Durability Project:

- Current Project involves development of knowledge base and preliminary tool for evaluating durability of glazing units,
- Develop novel approach to combine real-time simulation, built into the current tool SEALSIM, and FMEA methodology, developed during the phase I of the current project, so that the tool could be used in life-time prediction as well as failure mode analysis,

Proposed Flow Charts for the future Development:




Data Bases
Optical properties
Thermophysical
props
Weather data
Other?
TNO
SealSim
Report
Generator
(dll)
TNO
SealSim
MonteCarlo
generator
(dll)
IGU Durability Simulation
Computer Program GUI
FMEA – Real
Time
Simulations
Integrator
(dll)
Integrated
2-D/3-D
thermal,
structural,
diffusion model
(dll)
LBL
MultiPaneOptics
Center of glass
optical
properties
program
CAD Program
or 2-D/3-D
geometry
generator
LBL
W5cog.dll
Center of glass
thermal
analysis

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"Real-time simulations of the durability of Insulating Glass Units"

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ABSTRACT

The current methodology of reliability modeling and simulations is dominated by qualitative analysis methods. The methods include Failure Modes and Effects Analysis (FMEA), event tree diagrams etc. Quantitative analysis is mostly done by measurements in the field and in the laboratory (such as the methodology of Accelerated Ageing testing). These real-time methods usually require relatively long time of observations and are impractical in terms of providing fast feedback in the design process.

In recent times, the availability of significant and inexpensive computational power made it possible to consider real-time simulations of the relevant physical processes as major tools in the design and engineering of systems. In this paper, a computational simulations based methodology for quantitative analysis of durability (reliability) of Insulated Glass Units (IGU), is presented.

The physical model of IGU is given by a set of coupled differential equations. Thermal, structural and mass diffusion models are solved simultaneously for a given time period and for a given time step. The simulations are real-time and a proper choice of time-step unit can provide results equivalent to extremely long field observations. The failure modes are identified and incorporated in the model. The results of the simulations are subject to life data analysis. Right censored life data analysis is used as a natural choice for real-time simulations.

The possibility of utilization of real-time simulations for FMEA is discussed. Real-time simulations can be used selectively on separate units of the system. This way, the probabilities of failure of separate units can be estimated and can be incorporated in the FMEA. Real time simulations therefore can provide a method for obtaining additional quantitative accuracy in the qualitative methodology of FMEA.

KEYWORDS

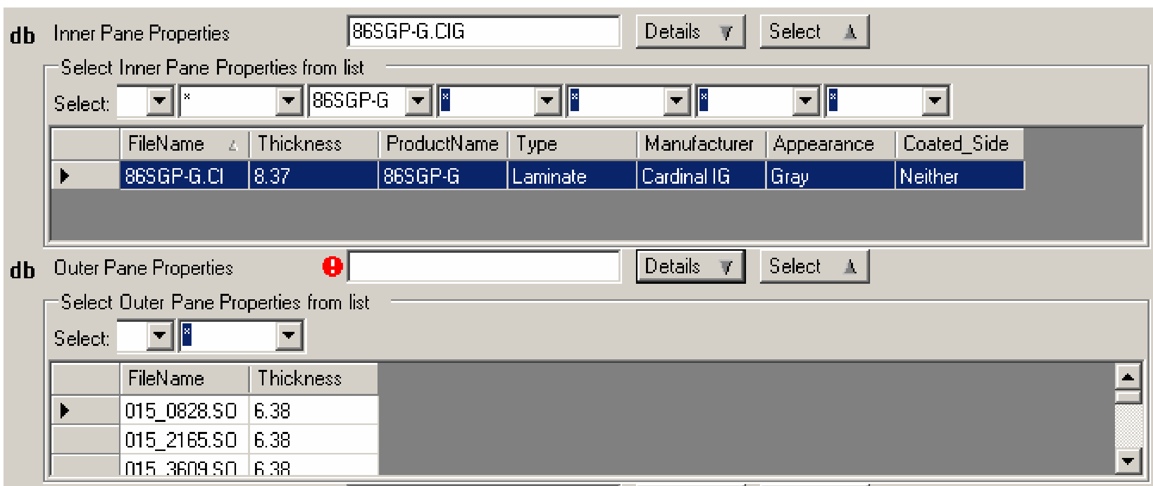
Insulating Glass Units, Real-Time Durability Simulations, Event-Tree Diagrams, Life-Data Analysis.

Appendix I. Cumulative Comments on Sealsim Program:

SEALSIM comments (second round):

Date: 2/12/04

- Creation date can not be set manually, but has to be specified through “calendar” pop-up. Also, one can set future date, which should not happen.
- Pane properties (selection from the db): the filtering does not work properly. If I select, for example 1.8288 mm glass and then try to select by manufacturer name, it gives me full list of manufacturers, not just ones that offer 1.8288 mm, so I end up with nothing. I think that it would be better if sorting similar to the one in W5 is done, where one can sort by fields (i.e., thicknesses, manufacturers, IDs, etc.)
- Default for both panes should be to show list of available glasses
- Outer pane does not have same list of properties as inner pane



- What is “Glass Material” selection?
- Gas fills still do not include defaults for Air, etc.
- For Seal and Wet Seal, some of entries are not clear. Need to start providing explanations and include some defaults (i.e., wet seal width, wet seal height, etc.)
- In initial conditions screen some entries are still half visible
- I have selected box spacer, but the filed for “Weight Fraction Desiccant in TPS” is still active
- Some entries do not have input fields (e.g., Initial total pressure gas space, etc.)
- For wind force, it asks for density of air. This should be automatically calculated based on temperature and pressure

- Instead of end of simulation filed, it would be better to specify number of years for simulation.
- What is “Climate Year” field? If I input weather data file, this gives all information regarding climate.
- Some fields are still cryptic (e.g., Criterium 0 active, Criterium 1 active, tec.)
- Defaults are needed throughout

Overview of the SEALSIM development

Date: 8/19/04

I have been involved with the project from February 14, 2003 meeting at Aspen between Aspen, TNO, Carli, Inc., and Pando Technologies. Several discussions during the second day of meetings were centered around the ownership of the program. Michael Doll emphasized couple of times that DOE requires any code developed during the project to be made fully available and that full source code be delivered. There were some questions about the codes that were developed earlier and that might be used in this project. Specifically, TNO mentioned numerical code DIANA and indicated that they will need to check with TNO if the code could be used as a part of the program distribution. General consensus was that DOE would not require that third party codes by delivered as a part of the project, although there was still option open to have such code in a version that would be used internally. In my mind it was crystal clear that any source code developed as a part of the project would be fully transferred to the DOE and full source code provided.

Initial discussions about the simulation engine for SEALSIM program hinted that the program will include more flexible 2-D numerical models, which would allow for arbitrary definition of geometry and materials of the IGU. However, very soon it became apparent that such an approach would substantially surpass available resources, both financial and later computer (i.e., the program would take unacceptably long time to produce any meaningful results), so TNO has proposed fixed models of box and TPS spacer, with fixed geometry and then apply what they refer to as 1½-D models, which were essentially 1-D models with some consideration of the 2-D path that heat and mass transfer would take, as well as some simple considerations for the effects of frame on structural performance of IGU.

During the course of the project, TNO has incorporated WINDOW 5 center of glass thermal model and OPTICS solar-optical model, which were third party tools, but were both developed with the DOE funding, therefore being fully eligible to be included in a public domain version of the program. No other third party tools were used, to my knowledge, and remainder of the source code was developed during this project. In my role as coordinator and overseeing party for the code development, I have recommended that the code be developed in a modular fashion, consisting of dll objects (dynamic link library objects), so that each simulation module is called by the main program. This kind of programming is recommended as it provides for flexible and readable code and allows for easy incorporation of alternate models. My other request from the very beginning was to use as much of accepted industry tools as possible. Use of WINDOW 5 and OPTCIS 5 codes is a direct result of that. Initially, as we were debating the use of more sophisticated 2-D numerical tools, I was proposing the use of another DOE tool THERM, as well as Carli, Inc. third party tool SPACER, which works in conjunction with THERM. However as we decided that we can not afford to use 2-D numerical models, this was left as a future option. Again, having the program constructed in modular fashion would allow for easier upgrades in the future.

In my review of the source code for version 1.0 of SEALSIM, I have discovered that the code was written as one giant “linear” source code, without any modularity. This is departure from what we have discussed in the beginning and will significantly impede further program modifications and upgrades. Furthermore, the source code for thermal and solar-optical part was deconstructed and included inside this “linear” source code. Disturbing aspect of this code inclusion is that it lists TNO as author of the program. If left untouched this amount to thievery and copyright infringement. Specific instruction has been that WINDOW and OPTICS routines will be included as objects, so that future revisions of these codes can be handled a simple as replacing one dll with another, instead of having to rewrite SEALSIM engine.

I have learned lately that TNO wants to restrict any change of the tool, which in addition to the violation of the DOE requirement to have full ownership of the code, developed in the course of the project, also puts impossible requirement to authors of WINDOW and OPTICS routines that they can not change their own program. This creates very difficult situation and in my mind this needs to change and should become high priority. I recommend that before the program is accepted as a deliverable and contractor (TNO) is paid, the following needs to happen:

1. Code needs to be modularized
2. WINDOW and OPTICS routines need to be linked through approved dll modules (i.e., released versions of w5cog.dll and optics.dll)
3. Ownership of the program needs to change from TNO to joint between TNO and DOE
4. Rights to further modifications of the code developed during this project should be granted to both owners (i.e., TNO and DOE)

Comments about SEALSIM:

Date: 8/24/04

- After each run a pie chart of coded failure events is obtained. However, as for any statistical analysis, this result is meaningful only if enough of statistical data is collected. Enough generally means that the stochastic phenomena of interest is sampled to the point when the probability distribution obtained is approximately the same as the “true” probability distribution. In our case the user should be advised that he/she should perform additional runs until the pie chart stabilizes and the next additional run does not change the pie chart and the probability distribution in a significant way. (Of course one can ask now what significant means, but a common sense can be used in most cases). This comment is revised due to understanding that the tool is research level and is to be used by expert users, however, some kind of warning is advised.

- Prepare a template .inp file for the Box-spacer IGU too?
- The manual is missing a short "idiot proof" list of instructions, for the first time user, how to run the examples provided (for example: "Click of the file-tab and open the Example1.inp file which in the directory…) Again, this may not be strictly necessary as this version is more research oriented.
- "Save" needed (right now only "Save As" available)
- Bar graph disappears after switching the screen from sealsim program to next and back
- Interface can be quite slow (it takes sometimes minute or so to refresh even for 1 yr run)
- Mismatches in GUI vs. inp:
    - Spacer type (it is 0 or box type regardless of actual choice)
    - Temperature?
    - Composition of spacer assembly (weight fraction is not the same)
- Even though I saved file as example1a, it displays example1
- Is pane distance absolute value or increment change from initial? If it is absolute, should have max and min space as a percentage of initial. Same for U-factor.
- Re-running the program without exiting GUI does not display status bar. The interface kind of hangs until it finishes.
- If you don't save file there is no warning when you exit and you loose changes
- Glazing database would be good to be updated to include items from sealsim so that same version can be used for w5 and sealsim. Will also communicate to LBNL.
- Unit conversion issue: leave as is for now
- Monte Carlo Runs: Are they variations in climate data or material properties (clarified during conf call that climate data are not varied. Only material properties. Climate data would need to be varied outside of sealsim)?
- Suggest reshuffling of some sections in the manual (e.g., some physical models are given in section 4 and some in section 8). Charlie will send some suggestions separately
- What is the meaning of minimum sub iterations per time step?

- Under simulation control, what is the purpose of minimum iterations for submodels. Clarified during conf call that this is more for testing and debugging purposes. Suggestion to hide these things (or fix them) for release version
- Results are confusing. Left vertical axis shows # of Monte Carlo runs, but it does not spell this out, while right axes shows Years, which have scale that vary depending on the run.
- How to get sealsim.exe. Clarified during conf call: sealsim source code is not included for now.
- “Open” should open the whole project (input and output files). Right now if you open .inp file, you don’t have results. Also, if I open different .inp file, the program will still display results from the old .out file.
- Scale of Years on the right of the graph should probably be eliminated. Think some more about this…

Comments on SealSim 1.1

Date: 12/28/04

- Failed to open .log file with Ctrl+L. Ctrl+L keeps trying to open sls.log but fails? The .log file opens well with MSWord.
- After opening the input file climate data files not loaded even though the paths are correct. Had to do it manually for each file.
- A list of failure criteria to explain the failure codes should be easily available in the GUI. The user should not be forced to look at the manual each time he/she obtains results.
- Box spacer example should be prepared.
- The contents of the CaseFiles folder have changed since SealSim1.0. The section 2.3 of the manual should be changed accordingly.
- The issues of number of Monte Carlo runs sufficient for meaningful statistical analysis of the results is somewhat better addressed in the current user’s manual.
- It is not clear what numbers 1.0 or 2 stand for in the data tree in the IGU.
- The definition of the durability index and its relation to average life time should be given more attention in the manual. Recommendation: The part on life-time calculations in section 3.3 Chapter 9 Appendix should be expanded and included in Chapter 5 with a more detailed description of the statistical meaning of the results and the overall durability index. The definition of the durability index should be given more attention in the manual.
- Some of the data tree descriptions are truncated. The format should be corrected.
- The bug of the engine trying to open sls.out files is still present. If this happens at the beginning of a run the entire run fails after a while!

Appendix 9

Example: Specifications

Example

Engineering Specifications for
Insulated Glass Assembly with Metal Spacer, Dual Seal Type

Gerry Hendrickson, Michael Doll

Section I, Engineering Specifications

A. General Description

The insulated glass (IG) unit described by this specification is intended for a window application in a window unit, door, or building wall construction. This specification is not intended for refrigerator or freezer door applications. The IG unit consists of two or more glass panes in a configuration where the outermost panes enclose a desiccated airspace which provides the insulation for thermal separation of the environments on either side of the IG unit when mounted in a typical installation. A metal spacer provides the physical spacing between the outer two lites of glass. A desiccant material in either a bead form or a matrix form is contained within the metal spacer to absorb moisture in the airspace and to prevent internal condensation or fogging.

The internal airspace may contain air or a mixture of gasses to reduce heat loss. Typical gasses, in addition to, or in place of air, are argon and krypton.

The internal airspace is sealed with a primary sealant having a low moisture vapor transmission rate (MVTR) to prevent moisture from entering the airspace. When argon filled, the primary sealant also serves to prevent gas loss of the argon. A secondary sealant provides structural qualities to withstand the forces and stress that the unit may experience.

The glass lites may be clear or coated (a material which controls light transmission and/or reflectance) tempered, laminated, etc.

The IG unit is intended to be mounted in a wood, vinyl, or metal sash frame which protects the edges of the glass and shields the sealant area from moisture and UV light exposure. The sash frame also provides additional structural support for the IG assembly.

B. Ratings (apply to IG mounted in a typical sash frame)

1. Reliability

a. Minimum required life is a 10 year reliability factor of 0.900 which correlates to a cumulative total failure rate of 10% in ten years. (The 1 year reliability index is 0.9895, the 20 year reliability index is 0.810.)

b. End of life is considered when any one of the following happens:

The internal dew point exceeds -40 F in a 70 F ambient.

Internal fogging of the glass reduces light transmission by 5% in any 2-inch x 2 inch area.

c. Glass fractures from non-impact events.

2. Structural design pressure

U.S. NWWDA	I.S. 2-93. DP 40
Canada	CAN/CSA A440-M90

3. Heat loss/gain (Argon , 90% filled)

Application	Residential		Non-Residential	
Unit size basis	24 x 48		30 x 60	
	U”	**“R”**	**“U”**	**“R”**
IG clear	.46	2.2	.46	2.2
Low E	.30	3.3	.29	3.4

Testing performed per: CAN/CSA A440.2
NFRC 100-91
ASTM C1199-91
ASTM E1423-91

4. Solar heat gain coefficient (Argon, 90% filled)

Application	Residential	Non-Residential
IG clear	.58	.57
Low E	.34	.35

Testing performed per: CAN/CSA A440.2
NWWDA/NFRC 200

5. Certification

The IG units (without sash frames) shall meet the requirements of ASTM E-2188 and E-2189.

IG assemblies must meet Sigma and NFRC requirements

C. Other Data

The complete set of specifications to govern with this product includes the following:

Material Specifications

(Gasses, Sealants, Desiccants, Spacer Materials, Glass, Etc.)

At a performance level, the engineered material specifications are defined by ASTM standards specific to the material properties of interest. The ASTM standards include acceptable variances. On the manufacturing floor, included is the specific material chosen (there can be optional materials but all must be shown) to meet the performance requirements. Additional specifications might include material color, packaging, etc., and other requirements which must be met for the chosen processing methods being executed. Each of these requirements will have a statement of acceptable variance as necessary. **The goal with any product or engineering specification is to create a set of documents that provide a comprehensive statement or definition to a level of resolution so that from the raw materials to the shipment of the final product no assumptions are made concerning any item or process.**

Detailed Piece Part and Assembly Prints

The part and assembly drawings are created as a performance specification is translated to a prescriptive specification to be used on the manufacturing floor. They are a large part of the recipe that was designed and developed to meet the performance specification. Just as in baking a cake, there is usually more than one way to meet the performance specifications and product expectations. As the choices are made (and changed over time) the documentation (drawing, specifications, etc.) are created to define and communicate the recipe for successfully assembling the IG. When an organization expects to implement high volume, repeatable processes these documents, a repeatable recipe are vitally important.

A description of an example drawing set which parallels the recommended design process would start with the final assembly drawing which ultimately describes the product as it will be shipped. In the case of an IG, expect to see final dimensions and their acceptable tolerances, statements of coating type, color, position etc, acceptable sightlines, sealant color and position; a complete description and the acceptable variance of the product. The description also may include:

A detailed, dimensioned graphical representation of the final product, The performance requirements listed in section #1 of this example specification,

The immediately required subassembly descriptions (numbers) required for final assembly

The immediately required part descriptions (numbers) required for final assembly

The immediately required materials for final assembly (gas for fill)

Process requirements and descriptions for final assembly

Company, patent and copyright information may also be presented

Any level of drawing (material, part, assembly, etc.) can, and usually is, tied directly to the final assembly drawing. Packaging drawings are tied to the final assembly drawing to define the relationship of the packaging (for shipment, distribution, retail sales, etc.) to the final product.

Sub assembly and component drawings are for many products the vast majority of drawing at the next level down. These drawings can expect to present any and all of the elements listed above but specific to the subassembly of interest.

At the bottom level are the incoming material drawings or specifications. If the product being produced is a material, then the bottom level will be the list of raw materials needed to complete the recipe. If the product is an assembly using component parts fabricated at another's facility, the bottom level drawing will be a part drawing containing the required information (performance and prescriptive) for use in the manufacturing assembly process.

For many products, added value processing is the majority of the product or engineering specification. An IG sealant material would be an example. Along with a set of performance specifications and the raw material specifications, the subsequent processing (compounding) of the material creates the expected product delivered. In contrast, for an assembly created from a series of component parts a larger majority of the specification is communicated through part, subassembly and final assembly drawings.

The process engineering specifications are a critical part of the IG, or any, engineering specification. If the engineering assembly, part drawings and material specifications are the ingredients of the recipe, the process specifications are the instructions for putting the ingredients together.

Section II, Process Specifications

Process Requirements

A. Control and manufacturing requirements

Glass to be cut to ES IG101 requirements

Coated glass to be edge deleted per ES IG102 prior to assembly

Apply logo per ES IG110

Wash glass per ES IG103

Apply primary sealant per ES IG105

Apply secondary sealant per ES IG106

Handle glass per ES IG104

Form and assemble spacer per ES IG109

Press glass and spacer assembly together with a minimum force of 0.3 lbs per inch of spacer length.

Gases fill (if required) per ES IG107.

Apply sealant to outer surface of spacer to a minimum depth of .1875 inch. Per ES IG106

Identify unit per ES IG111

Date code per ES IG112

B. Performance, Visual, and Special Requirements

Spacer and primary sealant to be free of finger marks and detritus in glass contact area.

Sealant to have no voids or air bubbles visible

Sealant to be visibly in contact with the glass around the entire perimeter of the unit

No sealant allowed on outer surface of glass

No sealant to extend beyond outer edge of glass

IG to have internal dew point below -80 F 24 hrs after final seal

No visible marks on internal glass surfaces.

Appendix (Listing of other Engineering records or documents

Glass, clear	MS IG1001A
Glass, Low E	MS IG1001B
Glass, clear, tempered	MS IG1001C
Glass, Low E, tempered	MS IG1001D
Glass, clear, clear, laminated	MS IG1001E
Glass, clear, low E, laminated	MS IG1001F
Sealant, primary, PIB	MS IG1002A
Sealant, secondary, polyurethane	MS IG1003A

Desiccant, bead type	MS IG1004
Spacer, aluminum	MS IG1005
Detergent, glass washing	MS IG1006
Fill gas, argon	MS IG1007
Fill gas, krypton	MS IG1008
Water, glass washing	MS IG1009
Glass separation beads (Lucor)	MS IG1010

Glass Cutting	ES IG101
Glass Edge Deletion	ES IG102
Glass Washing	ES IG103
Glass Handling	ES IG104
Primary sealant	ES IG105
Secondary sealant	ES IG106
Gas Filling	ES IG107
Glass Tempering	ES IG108
Spacer forming	ES IG109
Logo	ES IG110
Identify unit	ES IG111
Date code	ES IG112

IG reliability test	ES IG201
IG unit, dual seal, metal spacer	ES IG202

General assembly drawing	DR XXXX
Glass, cut	XXXXX
Spacer profile and detail	XXXXX
Spacer, formed	XXXXX
Logo design	XXXXX
Logo placement	XXXXX

Tooling drawings

Glass cutting wheels	XXXXX
Spacer bend fixture	XXXXX
Etc.	