SIMULATION ASSISTED RISK ASSESSMENT: BLAST OVERPRESSURE MODELING

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SUMMARY/ABSTRACT

A probabilistic risk assessment (PRA) approach has been developed and applied to the risk analysis of capsule abort during ascent. The PRA is used to assist in the identification of modeling and simulation applications that can significantly impact the understanding of crew risk during this potentially dangerous maneuver. The PRA approach is also being used to identify the appropriate level of fidelity for the modeling of those critical failure modes. The Apollo launch escape system (LES) was chosen as a test problem for application of this approach. Failure modes that have been modeled and/or simulated to date include explosive overpressure-based failure, explosive fragment-based failure, land landing failures (range limits exceeded either near launch or Mode III trajectories ending on the African continent), capsule-booster re-contact during separation, and failure due to plume-induced instability. These failure modes have been investigated using analysis tools in a variety of technical disciplines at various levels of fidelity. The current paper focuses on the development and application of a blast overpressure model for the prediction of structural failure due to overpressure, including the application of high-fidelity analysis to predict near-field and headwinds effects.

INTRODUCTION

Under NASA's Computing, Information, and Communications Technology (CICT) Program, several Grand Challenge Applications (GCA) were selected over a spectrum of problem types in an effort to drive end-to-end information technology development. In support of the CICT/ GCA objectives, a number of computational modeling and simulation tools suitable for application to the scenarios involved in crew abort were developed and/or mature codes were enhanced over the past several years. Demonstration cases involving elements of the abort process have been computed in support of requirements specified by Space Launch Initiative/Orbital Space Plane (SLI/OSP) industry partners; however, these requirements have tended to be specified in a relatively ad hoc manner. Out of these efforts came a perceived need for a more systematic methodology to identify the most relevant problems and the required level(s) of fidelity.

During the past year NASA Ames and NASA Glenn civil servant and contractor personnel have collaborated on the Simulation-Assisted Risk Assessment (SARA) project. The primary objective of the project is to integrate high-fidelity and engineering-level multi-disciplinary analyses in response to requirements defined through the application of Probabilistic Risk Assessment (PRA, e.g., see Ref. 1) modeling. PRA represents a systematic methodology for identifying and quantifying risks that could provide valuable guidance in the assessment of competing crew safety concepts. These methods involve the development of risk models that establish relationships and dependencies among system components and the accumulation of failure data for these components. In the simplest approach, a failure database represents the interface between the system-level model of the process being addressed and the available relevant modeling and simulation tools and processes. The application of uncertainty and sensitivity analyses to the failure database can be used to identify gaps and/or weaknesses in the failure data and, consequently, requirements for analysis and/or testing.

The Saturn V/Apollo ascent abort system was considered a suitable and relevant system for demonstration of the process given the current Crew Exploration Vehicle (CEV) concept. Although crew abort systems have been in place for capsule systems since the Mercury program[2], these flight programs accepted substantial risks because of the technological and schedule limitations imposed on them. For systems with long operational histories, failure data may be available from experience, but for fundamentally new systems or systems with little operational history, modeling will almost certainly be required to either create failure data from scratch or to extrapolate failure data from surrogate systems. Because of the limited testing and operational application of capsule abort systems, any systematic assessment of the risk of a CEV capsule abort system is likely to require a substantial amount of modeling and simulation to support the failure database. Because many of the understood risks of the Apollo abort process involve complex aerodynamic effects and interactions, it was felt likely that the high-fidelity computational tools and processes of the type developed under CICT/GCA would be especially valuable.

The development of data suitable for use by the PRA involves more than a few exploratory simulations and this poses a challenge for the application of high-fidelity methods. Therefore, even given the enormous resources of the Columbia computer system at NASA Ames Research Center, engineering-level methods are relied upon heavily in the process. One of the challenges of this project has been the development of a strategy for application of simulation tools of different levels of fidelity in such a way as to take best advantage of the strengths of the various tools. This paper will focus on the manner in which this was done in application to the problem of determining the risks of crew module structural failure caused by blast overpressure associated with the catastrophic failure of the launch vehicle.

RISK MODEL DEVELOPMENT

The first step in this project was the development of a high-level description of the abort process that contained the necessary logic to relate component-level failure modes to failures of the process or system, what was referred to as the risk model. The process consisted of: 1) determining the observed and potential failure scenarios associated with the Apollo Launch Escape System (LES), 2) developing a logical structure capable of representing these failure scenarios with a minimum number of basic events, and 3) capturing the structure in available PRA/fault tree software.

In order to develop an understanding of the Apollo Launch Escape System sufficient to develop a PRA structure representing the abort process, an extensive literature search was performed for documents on the Apollo program in general and the Apollo LES in particular. The collection currently comprises over 160 documents of various types, including technical reports, system description documents, system requirements documents, operations manuals, press kits, and interviews with key personnel. More than a dozen disciplines are represented. A spreadsheet-based database is maintained that tracks titles, authors, publication dates, disciplines, Mach regimes (for wind tunnel tests, etc.), configuration, etc. Not all reports included in the catalog are specifically Apollo-related, but all have been judged relevant to the problem in some respect. Outside risk experts were also consulted and they provided additional failure scenarios.

PRA Structure

Initially, the ascent abort risk model was cast as an event tree in which the abort process was abstracted into a series of “gates” or pivotal events that must be negotiated in order to have a successful abort (see Fig. 1). Each of the pivotal events was then supported by a fault tree - a logical structure linking the pivotal event to possible subsystem-level failure modes. As described in the previous section, a literature search for information regarding the design, testing, and operation of the Apollo LES provided much of the understanding of the potential risks in the abort process. Experience obtained during work on the Space Launch Initiative/Orbital Space Plane program and dialog with external risk experts provided additional inputs to the PRA model development. The preliminary event tree contained seven pivotal events represented by seven “gates” that must be negotiated to complete a successful abort. Fault trees were developed to break the event failure rate into potential component-related causes of failure. For example, the “Failure to Survive Explosion” event is broken into three causes as shown in Fig. 1. Approximately three dozen failure modes were identified. These represent the connecting points between the risk model and the failure database; that is, the failure database supplies the probabilities of failure for each of these modes.

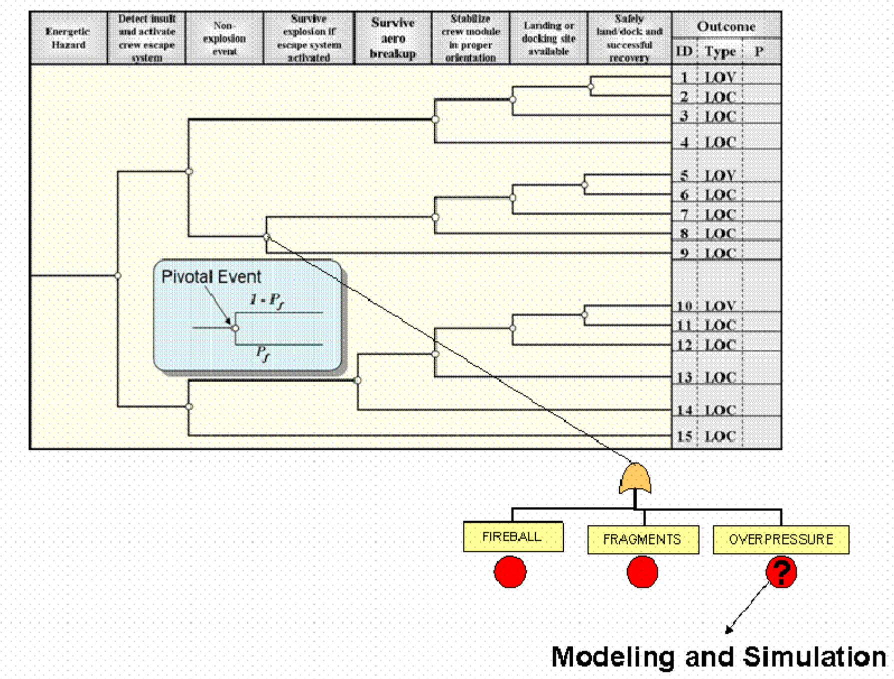


Figure 1. Conceptual risk model.

As experience with the model and the problem was acquired, weaknesses with the event tree modeling approach were observed. The main weaknesses were associated with the static nature of the model as compared to the highly dynamic nature of the ascent abort risks. The probability of failure at each of the gates was observed to be quite sensitive to the vehicle state and condition at the time of abort. As an example, the risk of failure due to blast wave-generated overpressures declines markedly as the launch vehicle accelerates beyond the point of maximum dynamic pressure. Then, even if the capsule survives the blast overpressure, it may be left in a state that is susceptible to aerodynamic instability. For these reasons, the risk model was recast as a single fault tree. The revised model incorporated time-varying rates for the likelihood of an abort as well as for the factors that determine abort success. This model was then enhanced to enable predicting the impact of false positive signals in which an abort is triggered even though the vehicle is operating normally. This feature is particularly important when trading the reliability of an ISHM system against the performance (i.e. lead time available) of the system. In addition, all of the failure probabilities were incorporated in a way as to allow for uncertainty measures to be included. The uncertainties are also permitted to vary with time, and are incorporated via a Monte Carlo analysis module included within the PRA. The PRA produces time varying mean risk intensity plots, an integrated system risk number, and the uncertainty distribution about the integrated estimate.

Currently, we are evaluating the potential advantages of recasting the model once again, this time within a significantly enhanced version of the SAFE software[3]. This approach holds promise of providing even more realistic modeling of the risks by enabling the user to provide functional relationships between the contributing failure modes and the vehicle state and to represent interdependencies between failure modes.

Failure Rate Development Process

Computing failure rates using high-fidelity modeling and simulation tools is a somewhat different type of application than is typically performed by computational researchers. In order to mitigate some of the confusion associated with this, an effort was made to generate a reference process, or template, for the computation of the failure rates.

This process begins by identifying the type of analysis required; more often than not, this analysis is some type of trajectory simulation. A sensitivity analysis is used to identify important input parameters to this process and probabilistic models for these inputs are generated. Failure criteria are established based on the system requirements. Uncertainty bounds can also be applied to the failure criteria. Typically a Monte Carlo approach is applied to combine the effects of multiple uncertain inputs into an output distribution. Finally, this output distribution is compared with the failure criteria to compute a failure rate. If the output constraint is uncertain, an uncertainty in the failure rate is also generated.

If data from the Apollo program was available or relevant surrogate data could be used, the first step in the process was to use the current tool set to reproduce that data. This validation exercise provided an understanding of the process required to perform the analyses, identified problems in the current codes, and occasionally identified problems in the historical data.

Depending on the type of analysis process required, the sensitivity and Monte Carlo analysis could lead to compute requirements capable of overwhelming even the massive resources of the Columbia system. For this reason, an effort has been made to identify and make use of efficiencies in the process, such as lower fidelity models, when appropriate.

A particularly good example of an application of the process can be found in Ref. 4 for the problem of determining the probability of experiencing trajectory range violations following abort separation.

BLAST OVERPRESSURE MODEL

Model Structure

For the Saturn V/Apollo launch system, one of the more prominent failure modes analyzed was the possibility that catastrophic failure of the booster leading to detonation of the propellant could create blast wave overpressures sufficient to fatally damage the crew module. In order to generate failure probabilities attributable to this mode and provide other data and insight into the design parameters that critically impact the ability to survive this failure mode, simple engineering-level models were developed or adopted for the phenomena associated with this process. The components and inputs involved in the analysis of this failure mode are shown schematically in Fig. 2. The failure scenario couples models for explosive blast overpressure propagation with a simple LEV trajectory model to determine the overpressure experienced by the escaping crew module. This

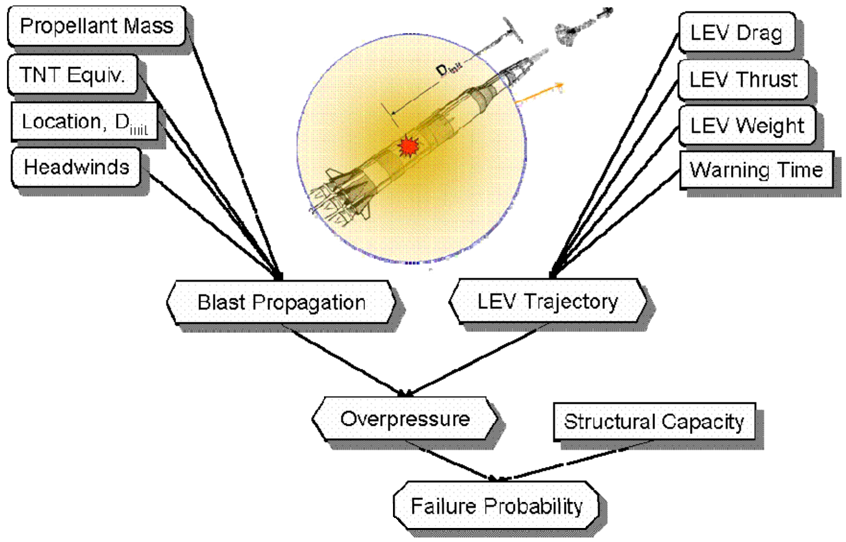


Figure 2. Blast overpressure model components.

overpressure is compared with the capsule's structural capacity to determine failure status. Both the blast and LEV propagation modules depend on multiple sub-components and/or inputs as shown in Fig. 2. Most, as indicated by the rounded rectangles, are directly or indirectly dependent on the trajectory and the time of abort. Figure 3 illustrates an example of the manner in which the blast propagation and LEV trajectory are intersected to determine the resulting overpressure experienced by the escaping crew module. Inherent in this model is the assumption that the blast does not interact with the LEV, i.e., that the blast overpressure associated with the blast is not significantly altered by the presence of the LEV. This assumption is understood to be of questionable validity and will be subject to modification in the future through the application of higher-fidelity simulation. The following sub-sections describe the most critical components of the scenario modeling.

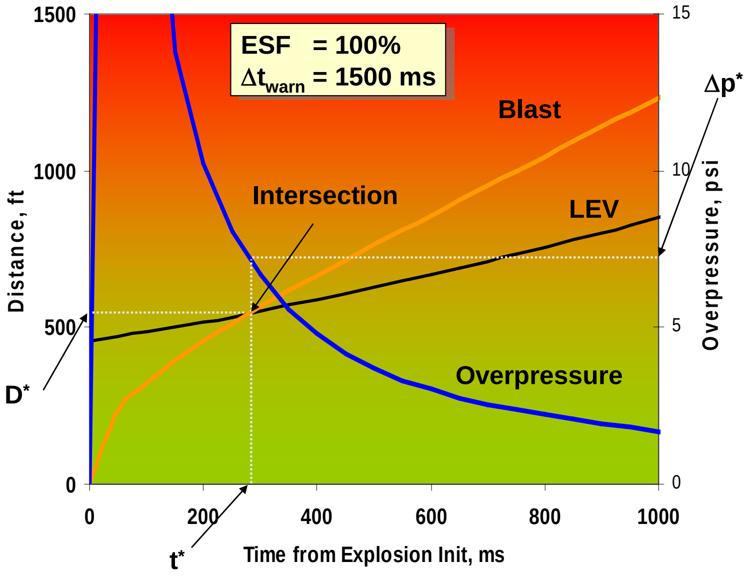


Figure 3. Illustration of trajectory intersection.

TNT-Based Blast Propagation

At the core of the engineering method is the TNT blast propagation model. Shown in Fig. 4, it consists of a tabulated version of Brode's axisymmetric 1-ton TNT simulation result[5] non-dimensionalized using Sachs scaling[6], which enables the extension of the model to include altitude and explosive energy variation effects. Sachs scaling relates the dimensional and non-dimensional parameters as follows:

Overpressure: $OP = (p_{max} - p_\infty)/p_\infty$
Distance: $\lambda = x/\alpha$, where $\alpha = (E_{prop}/p_\infty)^{1/3}$
Time: $\tau = t\, c_\infty/\alpha$, where c_∞ = ambient speed of sound

In these equations, E_{prop} is the energy of the blast and is computed, using the TNT equivalency approach, as a linear function of the existing propellant mass:

$$E_{prop} = \eta_{prop}\, m_{prop}\, E_{TNT}$$

Here, m_{prop} is the mass of propellant in tons and E_{TNT} is the energy associated with one ton of TNT ($4.2\text{x}10^9$ J is used in the current model). A critical parameter in this model is the equivalency factor of the explosion, η_{prop}. This parameter is a strong function of many factors, including propellant type, mass, and scenario (level of mixing, containment, etc.). As a starting point, values used early in the Apollo program[7] were applied for the propellant types involved in the Saturn V booster: $\eta_{LOX/RP1} = 0.1$ and $\eta_{LOX/H2} = 0.6$. Determination of more realistic TNT equivalencies was the subject of a fair amount of discussion and research at NASA Glenn Research Center (see Ref. 8). The above values were recognized at the time as very uncertain, and probably very conservative, and remain uncertain for the simple reason that they are so dependent on the factors listed above. This is an indication of the weakness of the TNT equivalency method for deterministic predictions; however, it has still proven useful in the investigation of trends and sensitivities to design parameters of the abort system. For solid rocket boosters, the TNT equivalence is provided by a pressure vessel bursting-type function of chamber pressure and internal volume and, as such, is a function of time-of-abort.

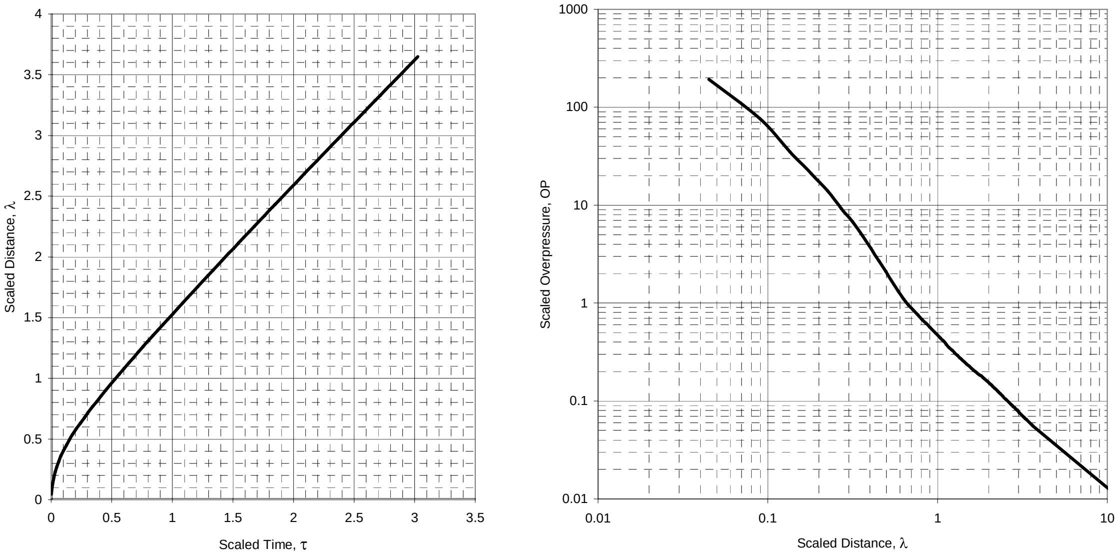
Another recognized weakness of the blast model is the near-field behavior, where the overpressure associated with high energy initiators such as TNT are known to be significantly higher than those associated with more distributed sources such as fuel-air detonations. Consequently, the TNT-based model is generally considered to provide a pessimistic view of the threat due to blast overpressure, at least in the near-field of the blast. Additional discussion of this point will be provided in the Application of CFD Methods section.

Headwind Effects

Along the ascent trajectory, the blast propagation process is influenced by the reduction in ambient pressure with increasing altitude, the reduction in fuel mass with engine burn time, and the increasing effective headwind. These effects act to weaken and slow the blast wave. The ambient pressure effect is accounted for through the Sachs scaling described earlier, but the headwinds effect requires additional consideration. As a first attempt to model the headwinds, a simple coordinate transformation is applied which effectively assumes the detonation center freezes in space at the moment of detonation, i.e., it is swept backwards with the freestream relative to the moving booster. As a result, the trajectories of the headwind-affected blast, D_{HW}, and the quiescent blast trajectory, D_Q, are related by:

$$D_{HW}(t) = D_Q(t) - V_\infty t\ ,$$

where V_∞ is the launch vehicle velocity at the time of explosion. The most significant consequence of headwinds is the blowback of the blast as it weakens and slows to a velocity below that of the freestream. This results in a rapid



a) blast front propagation trajectory **b) blast overpressure decay with distance**

Figure 4. TNT propagation model.

reduction of the threat due to overpressure as the launch vehicle velocity increases to Mach 3 and above.

Computational simulations[9] have provided some insight into headwind effects not accounted for in the current approach and the possibility of converting these insights into a replacement for the current model is currently being investigated. Qualitatively, the simulations indicate an increased initial shock strength and increased penetration into the headwind, relative to the current model. Additional discussion of this effect will be provided later in the paper.

Launch Escape Vehicle Trajectory

The blast propagation model described is programmed using Excel® macros and is coupled to a simple, one-dimensional, constant-acceleration model for the escape vehicle dynamics. This model is based on a simple altitude-corrected model for the escape thrust and drag data as a function of Mach number for the launch escape vehicle (LEV). This drag information was obtained from the Apollo aerodynamic data book[10] and is for a vehicle at zero incidence without plume effects. Thrust at altitude, T_h, is related to sea-level thrust, T_{SL}, using the simple relation

$$T_h = T_{SL} + (p_{SL} - p_h)\, A_{x,exit}$$

where p_h and p_{SL} are pressures at altitude and sea level, respectively, and $A_{x,exit}$ is the axial component of the separation motor nozzle exit area. The variation of the axial component of weight with altitude is just $W_h = W\sin\gamma$, where γ is the flight path angle at the trajectory point of interest.

Results

Treatment of Uncertain Inputs

Inputs to the blast model often are subject to substantial uncertainty. In some cases, mean values with uncertainty distributions can plausibly be applied and the model then can be used to produce a failure rate with uncertainty. In cases where likely values for all the inputs cannot be specified with confidence, or where sensitivities to certain inputs are desired, "terrain maps" can be generated by performing the analysis for ranges of values for the desired parameters. For example, Fig. 5 shows the sensitivity of failure likelihood to combinations of warning time provided and explosive efficiency for a pad abort scenario (first stage detonation centered at the intertank region). Here, the explosive efficiency is defined as the percentage of the nominal η value (again, 0.1 for RP). Failure of the capsule boost protect cover is assumed to occur at a mean value of 6 pounds per square inch (psi) overpressure with a standard deviation of 2 psi. At this point, all that is needed to generate a failure probability are likelihood distributions for warning time and explosive efficiency. Even without this information, the sensitivity map provides some valuable insight into the regions of the parameter space that really affect the risk. Another input that has been the subject of these types of plots is the parameter D_{init}, the location of the detonation center relative to the initial crew module location.

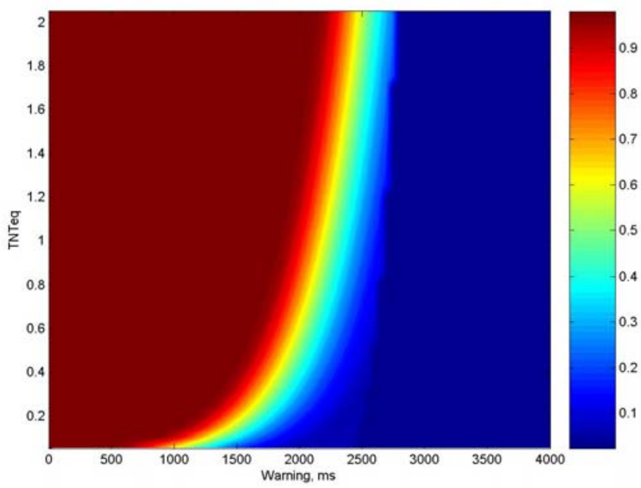


Figure 5. Overpressure failure probability sensitivity (pad abort)

Performance of trade studies is straightforward by replacing the either of uncertain inputs with a design parameter. For example, Fig. 6 shows the result of assuming a 10% TNT equivalency over a range of separation motor thrust levels at transonic conditions. Another example is shown in Fig. 7 which was produced by variation of the capacity of the structure to withstand overpressure.

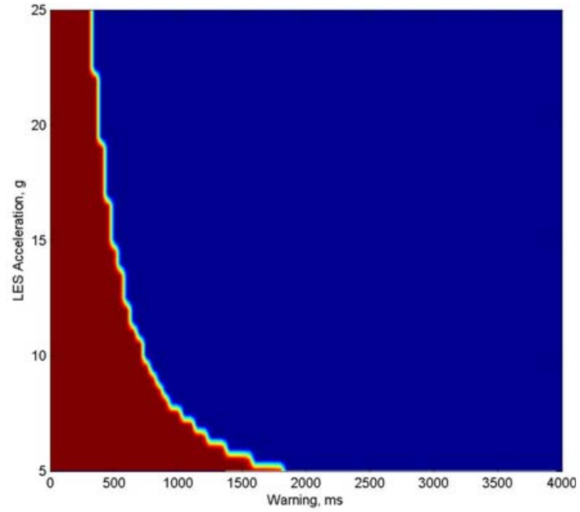


Figure 6. Escape motor thrust sensitivity (transonic abort)

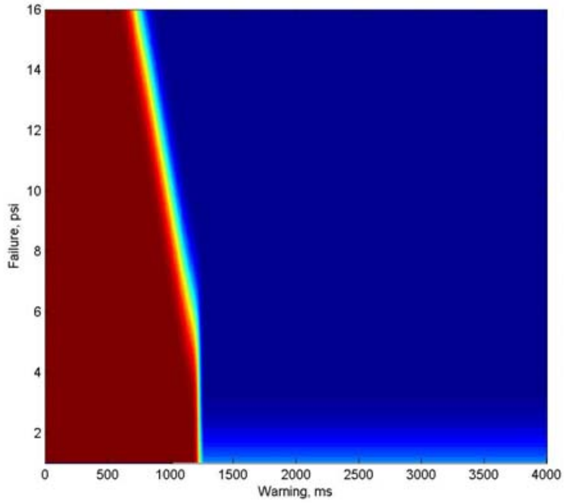


Figure 7. Structural capacity sensitivity (transonic abort)

Warning Time Predictions

Since the model is coded entirely within Excel, it is easy to reconfigure to solve for other parameters. One such application is the determination of warning times required to successfully separate to a “safe” distance. In this paper, the warning time is defined as the time before actual detonation that the launch escape system must begin to separate. Figure 8 shows computed warning times required as a function of ascent abort time. The failure scenario considered is complete involvement of the Saturn V first stage in the explosion ($\eta = 0.1$) with the detonation center at the intertank region. Three curves are plotted in Fig. 8: 1) required warning times published in Ref. 7, from the Apollo era, 2) current model results including headwind effects, and 3) current model with no headwind effects. Near the pad, ground plane reflection effects are accounted for by doubling the explosive efficiency. The two peaks in the distributions are associated with the large propellant mass at the pad and the high drag hindering separation near transonic and maximum dynamic pressure regions of the ascent trajectory. Based on these results, and on further inspection of additional data of Ref. 7, it is apparent that headwind effects were not included in data from Ref. 7. Agreement is reasonably good through the subsonic portion of the ascent. Reasons for the degrading comparisons at the higher altitudes have not yet been determined as the underlying data at those conditions were not published in the report.

Application of Computational Fluid Dynamics

Two recognized weaknesses in the integrated model are the headwind effects model and the over-prediction of the overpressure in the near- to mid-field of the detonation center associated with the TNT characteristic distribution. In order to examine the effects of the TNT-based model errors on the risk results, high-fidelity blast wave simulations were performed using the Overflow Navier-Stokes code[11], which are described in detail in Ref. 9. A series of simulations was initially performed to establish the ability of the analysis process to produce standard blast overpressure distributions for quiescent air. As can be seen in Ref. 9, the simulations produce lower overpressures in the near-field, but overpressures far from the detonation center agree well with the TNT distribution. As can be explained by use of the shock-tube formula, the near-field behavior is sensitive to conditions in the initiating high temperature, high pressure sphere. This is consistent with the knowledge that a universal distribution for the environment in the near-field of a fuel-air explosion does not exist. Development and use of a one-parameter family of curves representing varying detonation velocities could provide the next level of fidelity in modeling the near-field blast distribution. The practicality of such an approach is currently under investigation. Additional details are provided in Ref. 12.

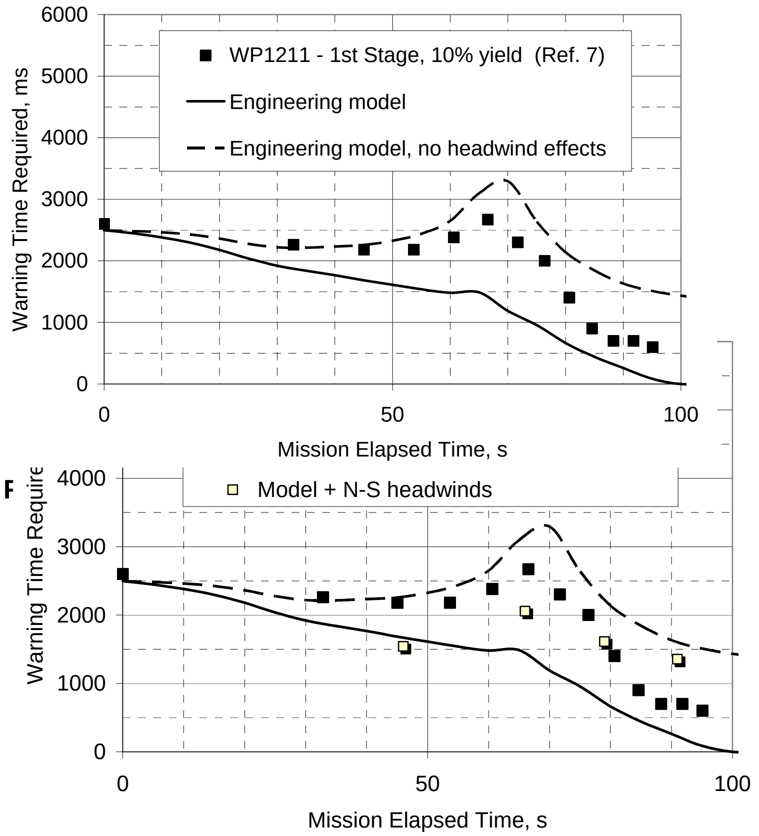


Figure 9. Effect of Navier-Stokes headwind simulations on warning time requirements.

In addition to the quiescent blast cases, Navier-Stokes simulations have been performed for determining the effect of headwinds on the blast propagation process. As the blast propagates, it weakens, decelerates relative to the freestream, and is finally blown backwards. The Navier-Stokes simulations predict a region of significantly increased overpressure prior to the blast wave being pushed back by the headwinds. Since the current interest was in the impact of these types of differences in the abort risk, the simulation data was used to replace the TNT blast and headwinds propagation models and the required warning times were recomputed at a few discrete Mach numbers. These are plotted as the open symbols in Fig. 9. The current results indicate a significant impact of the simulation-based headwinds on required warning time, especially in the transonic to supersonic speed regime; however, additional work remains to fully understand the importance of the initial conditions of the sphere used to start the Navier-Stokes simulations.

Ultimately, it is envisioned that the TNT model can be replaced by families of curves, generated through simulations as described above, along with an improved model for headwind effects. This approach to utilizing high-fidelity simulations is thought to be preferable to simply performing simulations on an as-needed basis because it enables the rapid extension of the information to other situations for performing trade studies, risk analysis, etc.

SUMMARY

A set of tools and processes for the modeling and simulation of capsule abort events has been developed and integrated with probabilistic risk assessment methods for the evaluation of crew safety concepts. The capability has been demonstrated using the Apollo launch escape system and ascent abort approach, beginning with an extensive literature search for Apollo- and abort-related documents and ending with a time history of risk contribution from several potential failure modes. Failure modes considered during the past year included failure caused by booster explosion, failure associated with trajectory range limit violations, and failure caused by re-contact with the booster during separation. The model for blast overpressure has been used to determine sensitivities to input uncertainties and explore design parameter trade space as well as produce warning time requirements for booster failure detection systems. The importance of the problems that were identified for analysis through the use of the risk perspective has been verified by NASA leadership.

ACKNOWLEDGMENTS

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REFERENCES

[1] NASA, Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners. Version 1.1.

[2] Greensite, A. L., "Analysis and Design of Space Vehicle Flight Control Systems," NASA CR-835.

[3] Go, S., and Mathias, D., "Trade Studies of Space Launch Architectures using Modular Probabilistic Risk Analysis," International Conference on Probabilistic Safety Assessment and Management, May 14-19, 2006, New Orleans, LA (to be presented).

[4] Gee K., and Lawrence, S., "Probabilistic Assessment of Vehicle Launch Abort Trajectories," International Conference on Probabilistic Safety Assessment and Management, May 14-19, 2006, New Orleans, LA (to be presented).

[5] Brode, H. L., "Blast Wave from a Spherical Charge," *Physics of Fluids*, Vol. 2, No. 2, 1959.

[6] Baker, W. E., *Explosions in Air*, University of Texas Press, Austin, TX, 1973.

[7] Teixeira, C., "Warning Time Required by the Apollo Spacecraft to Successfully Abort in the Event of a Launch Vehicle Explosion," NASA TM-X64314, 1966.

[8] Claus, R., and Zampino, E., "A Proposed Approach for Estimating the Explosive Risk of Launch Vehicles," AIAA Paper 2006-1177, 44th Aerospace Sciences Meeting and Exhibit, Reno, NV, January, 2006.

[9] Olsen, M., Lawrence, S., Mathias, D., Klopfer, G., and Onufer, J., "Simulation of Blast Waves in Headwind," AIAA Paper 2006-0955, 44th Aerospace Sciences Meeting and Exhibit, Reno, NV, January, 2006.

[10] North American Aviation, Inc., "Aerodynamic Data Manual for Project Apollo," Report SID 64-174C, 1965.

[11] Buning, P. G., Jesperson, D. C., Pulliam, T. H., Klopfer, G. H., Chan, W. M., Slotnick, J. P., Krist, S. E., and Renze, K. J., "OVERFLOW User's Manual, Version 1.8aa," NASA Langley Research Center, April, 2003.

[12] Lawrence, S., Mathias, D., Klopfer, G., Pandya, S., Onufer, J., Holst, T., and Gee, K., "Simulation-Assisited Risk Assessment," AIAA Paper 2006-0090, 44th Aerospace Sciences Meeting and Exhibit, Reno, NV, January, 2006.