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ENCAPSULANT SELECTION AND DURABILITY TESTING EXPERIENCE

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ABSTRACT

The Flat-Plate Solar Array Project (FSA) has established technically challenging cost and service-life goals for photovoltaic modules. These goals are a cost of $70/m^2$, and an expected 30 years of service life in an outdoor weathering environment. Out of the cost goal, $14/m^2$ is allocated for encapsulation materials, which includes the cost of a structural panel. At FSA's inception in 1975, the cumulative cost of encapsulation materials in popular use, such as room-temperature vulcanized (RTV) silicones, aluminum panels, etc., greatly exceeded $14/m^2$. Accordingly, it became necessary to identify and/or develop new materials and new material technologies to achieve the goals.

Many of these new materials are low-cost polymers that satisfy module engineering and encapsulation processing requirements but unfortunately are not intrinsically weather-stable. This necessitates identifying lifetime and/or weathering deficiencies inherent in these low-cost materials and developing specific approaches to enhancing weather stability. In addition, relevant accelerated aging techniques must be developed to enable assessment of encapsulation system lifetimes. Specific items include the development of chemically attachable stabilization additives [ultraviolet (UV)-screening agents, antioxidants, etc.], computer-assisted kinetic modeling of outdoor weathering reactions, and the use of novel outdoor heating racks and controlled environmental reactors in accelerated aging techniques. Other encapsulation technologies related to life and durability include soiling, electrical insulation, and primers and adhesives.

Encapsulation Systems

The two basic encapsulation systems for terrestrial photovoltaic modules are the substrate system and the superstrate system. These design classifications refer to the method by which the encapsulated solar cells are supported mechanically. A substrate design has encapsulated cells supported by a structural backside panel, and in the superstrate design the encapsulated cells are supported by a transparent, sunside structural panel (e.g., glass). These two basic systems have up to nine material components, called construction elements. These are illustrated in a viewgraph, with their designations and encapsulation functions.

Low-cost candidates for the substrate panels are mild steel and hardboard; glass is the lowest-cost candidate for the superstrate panel. Plastic materials used structurally as either a substrate or a superstrate are considerably higher in cost. The low-cost candidate for the porous spacer is a non-woven E-glass mat. Low-cost candidates for all of the other construction elements are polymeric.

Polymeric Encapsulation Materials

Pottants. The central core of an encapsulation system is the pottant, a transparent, elastomeric material that is the actual encapsulation medium in a module. It totally encloses and embeds all of the solar cells and their associated electrical circuitry. The demands on a pottant material are numerous; some of the more significant requirements follow:

(1) It must be highly transparent in the silicon solar-cell response region of 0.4 to 1.1 μm.

(2) It must function as electrical insulation for isolating high-voltage circuitry.

(3) It must provide mechanical cushioning and stress media for fragile solar cells.

(4) It must be readily processable in automated module fabrication.

The cells and circuitry encapsulated with the pottant must be supported mechanically by either a structural substrate panel or a transparent structural superstrate panel. If supported by a backside (substrate) panel, the top surface of the soft elastomeric pottant must be covered with a hard, durable front-cover film to reduce soil accumulation. Soft surfaces have a greater tendency to retain soil than do hard surfaces. To identify the lowest-costing transparent elastomeric materials that could function as pottants, it was specified that the pottant material, either as is or with appropriate additives, shall be resistant to hydrolysis and thermal oxidation at temperatures up to 80°C, but UV sensitivity was allowed. This selection approach was predicated on the concept that the lowest-costing encapsulation systems could not isolate the elastomeric pottant from atmospheric moisture and oxygen, but that cost-effective UV filtering could be accomplished either by a glass superstrate or by the a low-soiling front-cover plastic film placed over the pottant on a substrate module.

Four pottant materials have emerged as most likely candidates and are currently in various stages of development or industrial use: ethylene vinyl acetate (EVA), ethylene methyl acrylate (EMA), poly-n-butyl acrylate (PnBA), and aliphatic polyether urethane (PU). EVA and EMA are dry films designed for vacuum-bag lamination at temperatures up to 150°C. Above 120°C during the lamination process, EVA and EMA undergo peroxide crosslinking to become tough, rubbery thermosets. PnBA and PU are liquid casting systems. PnBA, a polymer-monomer syrup, was developed jointly by JPL and Springborn Laboratories, Inc. PnBA is being formulated to cure within 15 minutes at 60°C. A commercial polyether urethane for pottant application is available from Development Associates, North Kingston, Rhode Island, marketed under the designation Z-2591.

Ethylene Vinyl Acetate. EVA is a copolymer of ethylene and vinyl acetate, typically sold in pellet form by Du Pont Co. and U.S. Industrial Chemicals, Inc. (USI) The Du Pont trade name is Elvax; the USI trade name is Vynathane. The cost of EVA typically ranges between $0.55 and $0.65 per pound. All commercially available grades of EVA were examined and the list was reduced to four candidates, based on maximum transparency: Elvax 150, Elvax 250, Elvax 4320, and Elvax 4355. Because EVA is thermoplastic, processing it into a module is best accomplished by vacuum-bag lamination with a film of EVA. Therefore, based on film extrudibility and transparency, the best choice became Elvax 150. Elvax 250 was an extremely close second choice.

Elvax 150 softens to a viscous melt above 70°C, and therefore is not suitable for temperature service above 70°C when used in a fabricated module. A cure system was developed for Elvax 150 that results in a temperature-stable elastomer. Elvax 150 was also compounded with an antioxidant and UV stabilizers, which improved its weather stability and did not affect its transparency. These ingredients are compounded into Elvax 150 pellets, followed by extrusion at 85°C to form a continuous film. The thickness of the clear film is nominally 18 mils. The selective curing system is inactive below 100°C, so that film extruded at 85°C undergoes no curing reaction. The extruded film retains the basic thermoplasticity of the Elvax 150. Therefore, during vacuum-bag lamination, the material will soften and process as would a conventional laminating resin.

This EVA pottant has undergone extensive industrial evaluation, and manufacturers of photovoltaic (PV) modules have reported certain advantages:

(1) Lower cost.

(2) Good appearance.

(3) Clarity.

(4) Non-yellowing.

(5) Obviates cold storage.

(6) Dimensional stability.

(7) Pressure autoclave not required.

(8) Good flow properties and volumetric fill.

Although this encapsulation-grade EVA has been favorably received by the industry, its status is still considered to be experimental. To advance EVA, several developmental tasks remain to be completed:

(1) Faster processing, primarily in the cure schedule, which involves a reduction in cure time and temperature; the minimum cure temperature will be dictated by the requirement that the curing system must not become active during film extrusion.

(2) Optimization of the UV-stabilization additives; the present additives were selected on the basis of literature citations and industrial experience with polymers similar to EVA.

(3) Identification of the maximum service temperature allowed for EVA in a module application to ensure long life.

(4) Industrial evaluation of the desirability of having a self-priming EVA, recognizing the possibility of an additional cost component (cost-benefit-performance tradeoff).

Consideration of these tasks has led to the development of an advanced formulation for EVA, designated 18170.

EVA Aging Studies. Elvax 150 can be degraded by UV photooxidation, thermal oxidation, and by purely thermal decomposition of the acetate groups to acetic acid. These degradation reactions are stated in order of decreasing severity, and as protection against each in order is provided, the life and associated peak service temperature of EVA encapsulant can be extended.

Fundamental analysis of Elvax 150 suggests that the UV wavelengths deleterious to this material, and necessary for UV photooxidation, are those shorter than 360 nm. Isolation of Elvax 150 from these UV wavelengths by means of UV-filtering outer covers and/or compounding additives such as Cyasorb UV-531 stops UV photooxidation and reduces the aging characteristics of Elvax 150 to thermal effects. This basic and very simple concept was established as a fundamental module-design philosophy, and no problem with this concept has been identified in the experimental aging results to date.

For example, testing of EVA samples in the RS/4 UV chambers at 55°C included the following combinations:

(1) Elvax 150 without any protection, either additives or UV-screening film overlays.

(2) Elvax 150 with a UV-screening film overlay, but with no antioxidant or UV-absorbing additives.

(3) Fully compounded and cured A-9918 EVA, with an antioxidant and UV-absorbing additives but with no UV-screening film overlay.

The Elvax 150 sample (No. 1) without any protection yellowed visibly and degraded within 1000 h of exposure, whereas samples Nos. 2 and 3 with UV protection as indicated have survived 20,000 h to 30,000 h of exposure without any degrading incidences. Accepting that the UV protection for the latter two samples acted to isolate or protect them from deleterious UV wavelengths, then their aging at 55°C was reduced to that of thermal aging. And further, as no aging effects were detected in these two samples, with or without an antioxidant, these tests indicate strongly that Elvax 150 at 55° either is naturally resistant to thermal oxidation, or undergoes negligibly slow thermal oxidation.

If it can be assumed that a module using Elvax 150 as a pottant provides the necessary UV protection, and if it can be assumed that such a module may be at or near a daily array peaking temperature of 55°C for about 5 h each day, then 20,000 h to 30,000 h of accumulated thermal aging in the RS/4 chambers corresponds to 11 to 16 years of potential outdoor service. For module applications having daytime peaking temperatures near 55°C, it appears that the life of the EVA encapsulant is related more to the life of the UV protection schemes and less to either the thermal behavior of the EVA or thermal protection schemes (for example, antioxidants).

Between 55°C and 93°C (200°F) there is no direct experimental or literature information on the thermal aging behavior of Elvax 150. Unresolved questions relate to knowing if a threshold temperature exists for Elvax 150, above which thermal oxidation begins, to knowing the temperature dependence of the rates of thermal oxidation of Elvax 150, and to knowing the effectiveness of antioxidants and the associated temperature dependence of their protective induction periods. Although the 10 mo (7200 hours) of thermal stability observed at 90°C for the dark-thermal aging of cured A-9918 EVA is encouraging, it is not known whether this is natural to the Elvax 150, or that 10 mo was still within the protective induction period of the antioxidant. In addition, the concentration of Cyasorb UV-531, a critical element of the UV protection scheme, was not monitored in these thermally aged specimens.

The potential for long service life of EVA in modules at rooftop temperatures (e.g., 85°C) looks encouraging, but predictions of lifetime would be premature. As at 55°C, UV protection and permanence of the UV protection are essential. After that, it is not clearly established which of the thermally driven processes is most critical. These processes include the basic thermal oxidation properties of the Elvax 150, of antioxidants and the associated temperature dependency of their protective induction periods, and the temperature dependence of any physical loss and depletion of the protective compounding additives themselves, such as the UV and thermal stabilization additives.

UV Screening Plastic Films. The module front cover is in direct contact with all of the weathering elements: UV, humidity, dew, rain, oxygen, etc.; therefore, the selected materials must be weatherable. Only four classes of transparent materials are known to be weatherable: glass, fluorocarbons, silicones and polymethyl methacrylate.

In addition to weatherability, the front cover must also function as a UV screen, to protect underlying pottants that are sensitive to degradation by UV photooxidation or UV photolysis. The outer surface of the front cover should also be easily cleanable and resistant to atmospheric soiling, abrasion-resistant, and antireflective to increase module light transmission. If some or all of these outer-surface characteristics are absent in the front-cover material, additional surfacing materials may have to be applied.

Excluding glass, the only commercially available transparent UV-screening plastic films that have been identified are fluorocarbon films (Tedlar, Du P[illegible], and PMMA films (Acrylar, 3M Co.).

Back Covers. Back covers are back-surface material layers that should be weatherable, hard, and mechanically durable and tough. Engineering analysis indicates that the color of the back-surface material layer should be white, to aid module cooling. Back covers function to provide necessary back-side protection for substrates, such as (for example) corrosion protection for low-cost mild-steel panels, or humidity barriers for moisture-sensitive panels. For superstrate designs, the back cover provides a tough overlay on the back surface of the soft, elastomeric pottant. If a metal foil is selected for the back cover of a superstrate design, an additional insulating dielectric film should be inserted in the module assembly between the cells and the metal foil.

Edge Seals and Gaskets. Trends based on technical and economic analysis suggest that butyls should be considered for edge seals, and EPDM elastomers should be considered for gaskets. Several materials for each application are under investigation. One of the more promising edge-seal materials is a butyl-edge sealing tape designated 5354 (3M Co.), and one of the more promising EPDM gasket materials is designated E-633 (Pawling Rubber Corp.).

Primers and Adhesives. Continuing FSA work on this encapsulation technology has resulted in the development of three general-purpose primers for all module interfaces. It should be pointed out that these primers are experimental, and that an assessment of their lifetime and durability is in progress. Results are extremely encouraging.

Electrical Insulation. A new concept has been developed regarding the possible definition of the intrinsic dielectric strength of insulating materials, which can be considered as a fundamental material property similar to Young's modulus, index of refraction, etc. The concept, if valid, provides an absolute material property related to electric insulation that can be directly monitored as a function of accelerated and/or abbreviated aging. This concept will be evaluated as part of the module life assessment studies.

Outdoor Heating Racks. A novel accelerated aging technique has been developed using outdoor racks on which test materials and modules can be heated to fixed temperature levels above ambient, to accelerate aging from exposure to the natural weathering elements, e.g., oxygen, UV, humidity and pollution. Trial outdoor aging tests are currently being carried out at 70°C, 90°C and 110°C. The outdoor heating racks are programmed to turn on at 6:00 a.m. to a preset temperature, and to turn off at 6:00 p.m. to permit test materials and modules to cool overnight. It is intended that the rates of change of material properties and module performance parameters monitored at elevated temperatures in the natural environment can be used to estimate ongoing rates at the lower temperatures associated with actual module performance.

A viewgraph shows polypropylene aging data measured on the these racks. Extrapolation of the higher-temperature aging data to ambient predicts an outdoor aging lifetime for this polypropylene of about a third to a half of a year. This is virtually the actual aging lifetime for unstabilized and/or unprotected polypropylene outdoors. With this satisfying observation, future work will shift to encapsulation materials, and to fully fabricated modules.

Low-Soiling Surface Coatings. Evolving soiling theories and physical examinations of soiled surfaces suggests that soiling accumulates in three layers. The first layer involves strong chemical attachment, or strong chemisorption of soil matter on the primary surface. The second layer is physical, consisting of a highly organized arrangement of soil matter effecting a gradation in surface energy, from a high associated with the energetic first layer, to the lowest possible state on the outer surface of the second layer. The lowest possible surface-energy state is dictated by the chemical and physical nature of the regional atmospheric soiling materials. After these first two layers are formed, the third layer constitutes a settling of loose soil matter, accumulating in dry periods and being removed during rainy periods. The aerodynamic lifting action of wind can remove particles greater than about 50 µm from this layer, but is ineffective for smaller particles. Thus, the particle size of soil matter in the third layer is generally found to be less than 50 µm.

Theories and evidence to date suggests that surfaces that should be naturally resistant to the formation of the first two rain-resistant layers are hard, smooth, hydrophobic, free of first-period elements (for example, sodium), and have the lowest possible surface energy. These evolving requirements for low-soiling surfaces suggest that surfaces or surface coatings should be of fluorocarbon chemistry.

Two fluorocarbon coating materials, a fluorinated silane (L-1668, 3M Co.), and perfluorodecanoic acid, are under test. The perfluorodecanoic acid is chemically attached to the surfaces with a Dow Corning chemical primer, E-3820. The coatings on glass and on the 3M Acrylar film are being exposed outdoors in Enfield, Connecticut, and the loss of optical transmission by natural soil accumulation is being monitored by the performance of standard solar cells positioned behind the glass and film test specimens. These test specimens are not washed. Twenty-eight months of test results are shown for glass and Acrylar.

After 28 months outdoors, soil accumulation on the uncoated glass control has resulted in about a 2.65% loss of cell performance, whereas the glass coated with L-1668 has realized only about a 1.59% loss. The glass sample coated with perfluorodecanoic acid has realized about the same loss. The uncoated Acrylar control has realized about a 7.20% loss, whereas the loss on the sample coated with perfluorodecanoic acid is only about 7.20%, and the loss on the Acrylar sample coated with L-1668 is about 4.2%. Similar results are obtained on the Tedlar samples. The test results indicate that compared with untreated controls, soil accumulation is being reduced on those test samples treated with the candidate fluorocarbon surface coatings.

Encapsulation Engineering. An engineering analysis of encapsulation systems has been carried out to achieve a reliable and practical engineering design. This analysis involves four necessary features of a module:

(1) Structural adequacy.

(2) Electrical isolation (safety).

(3) Maximum optical transmission.

(4) Minimum module temperature.

One of the goals of this analysis is the generation of guidelines for minimum material usage for each of the construction elements.

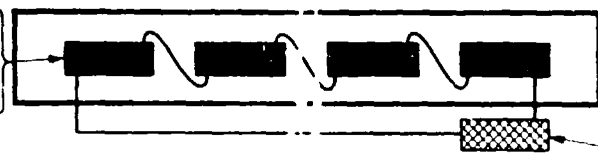
The analyses for structural adequacy showed that thermal expansion or wind deflection of photovoltaic modules can result in the development of mechanical stresses in the encapsulated solar cells sufficient to cause cell breakage. The thermal stresses are developed from differences in the thermal expansion properties of the load-carrying panel and the solar cells. However, the analysis showed, interestingly, that the solar-cell stresses from either thermal expansion differences or wind deflection can be reduced by increasing the thickness t of the pottant, or by using pottants with lower Young's modulus E. In other words, the analysis indicates that the load-carrying panel can be considered to be the generator of stress, and that the pottant acts to damp the transmission of the stress to the cells. The pottant's ability to damp transmitted stress is directly related to the ratio of its thickness to modulus (t/E).

For example, the analysis finds, for a 4-ft-square glass-superstrate module undergoing a 50 mph wind deflection, that the pottant t/E ratio should be equal to or greater than 4:1, where t is in mils and E is in units of klb/in.^{2}. At a ratio of 4:1, the solar-cell stresses are just at their allowable limit. If the pottant were EVA having a Young's modulus E of 0.9 klb/in.^{2} would necessitate that the thickness of that pottant be correspondingly increased. It should be mentioned that the t/E requirement of a glass-superstrate module undergoing thermal expansion is only 2:1. Thus solar-cell stresses generated by the wind deflection of a glass-superstrate module, rather than thermal expansion effects, dictate the minimum usage requirements of pottants.

This kind of output from the engineering analysis begins to enable a cost-comparison basis for candidate materials. For example, compared with EVA, a higher-costing pottant having a higher Young's modulus would be much more costly to use for reasons of both higher materials cost and the need for more thickness. On the other hand, a higher-costing pottant having a lower Young's modulus may be just as cost-effective due to an allowed thinner usage.

Advanced Thin-Film Encapsulation Concepts. The last four viewgraphs illustrate some advanced encapsulation concepts for thin-film photovoltaic modules. Essentially, the concepts involve direct coating of a liquid resin onto the cell surfaces, followed by photo-curing, or by electron-beam curing. A novelty is that the liquid resin is actually a mixture of immiscible polymer fluids that, before the curing phase, separate into layers, from a soft elastomeric inner layer to a hard, tough, and weatherable top layer.

Basic Components of a Photovoltaic Module



COST ALLOCATION (1980 DOLLARS) FOR PACKAGING MATERIALS

TOTAL MODULE COST = 70 CENTS/WATT $\approx$ \$7.00/FT^2 $\approx$ \$70.00/m^2

PACKAGING COST = 14 CENTS/WATT $\approx$ \$1.40/FT^2 $\approx$ \$14.00/m^2

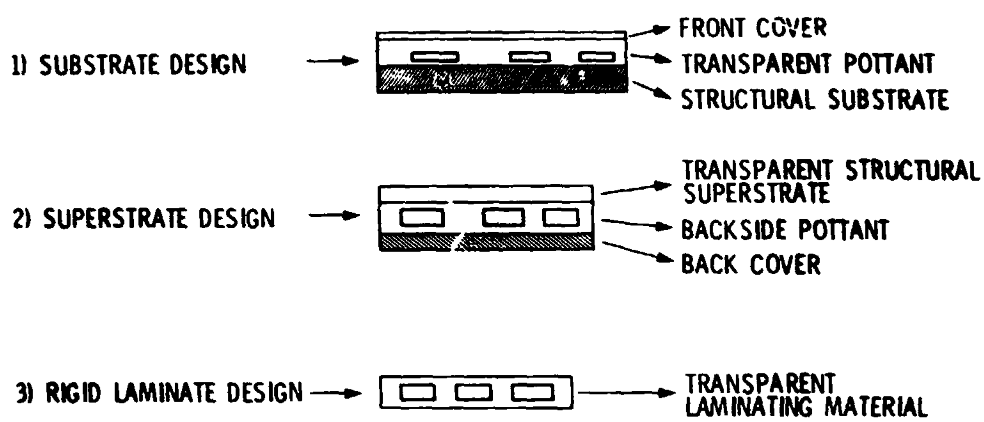
ALL ELSE = 56 CENTS/WATT

- CELLS
- INTERCONNECTS
- TERMINAL
- MANUFACTURING
- PROFITS
- TAXES

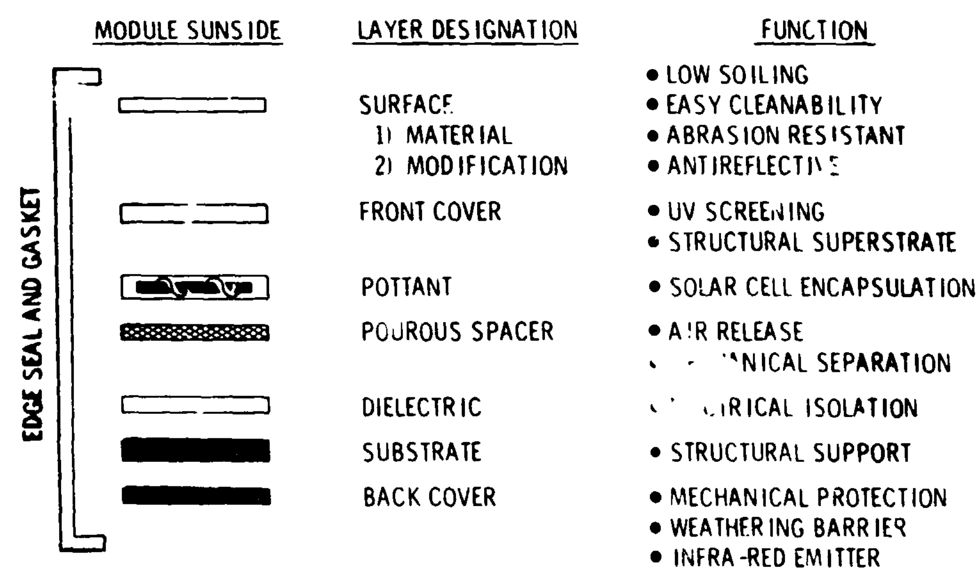
Encapsulation Requirements

• OUTDOOR LIFE	30 YEARS
• OPTICAL TRANSMISSION TO SOLAR CELLS	>90% OF INCIDENT
• LOSS IN MODULE POWER AFTER 30 YEARS	<10% OF INITIAL
• PROCESSING AND FABRICATION	AUTOMATED
• STRUCTURAL PERFORMANCE (INCLUDING HANDLING AND WEATHERING)	NO FAILURES

Encapsulation Design Classifications



Encapsulation Materials: Module Construction Elements



PLUS NECESSARY PRIMERS/ADHESIVES

Transparent Encapsulation Pottants

1. WEATHERING ACTIONS
   a. UV REACTIONS
   b. THERMAL OXIDATION
   c. HYDROLYSIS

2. COST/WEATHERING RELATIONSHIP

MATERIAL COST	WEATHERING ACTIONS
25¢ TO 65¢/LB	a, b, c
65¢ TO $1.00/LB	a (RESISTANCE TO b AND c, UP TO 80°C)
> $1.00/LB	NONE

3. CANDIDATE POTTANT MATERIALS
   a. LAMINATION FILMS
      ETHYLENE VINYL ACETATE (95¢/LB)
      ETHYLENE METHYL ACRYLATE (95¢/LB)
   b. CASTING LIQUIDS
      POLY-N-BUTYL ACRYLATE (85¢/LB)
      ALIPHATIC POLYETHER URETHANE ($\approx$ $3.00/LB)

Pottants: Evolving Specifications and Requirements

- GLASS TRANSITION TEMPERATURE < -40°C
- MECHANICAL CREEP RESISTANCE AT 90°C
- TENSILE MODULUS $\leq$ 3000 LB/IN.^{2} AT 25°C
- OPTICAL TRANSMISSION (0.4 TO 1.1 μm), > 90%
- THERMAL OXIDATION RESISTANCE AT 80°C
- HYDROLYSIS RESISTANCE AT 80°C
- UV REACTION SENSITIVITY < 350 nm
- CHEMICAL INERTNESS AT 80°C (COPPER, NICKEL, SOLDER, ETC.)
- WATER ABSORPTION < 0.5 WT % AT 20°C/100% RH

Front Covers for Substrate Designs: UV Screening Plastic Films

MATERIAL	COMMERCIAL COST	STATUS
1. ACRYLIC		
a. ACRYLAR X-22416, 2 MILS	≈ 4.8¢/FT^2	AVAILABLE, 3M
b. ACRYLAR X-22417, 3 MILS	≈ 6.7¢/FT^2	
2. FLUOROCARBON		
a. TEDLAR 100 BG 30 UT, 1 MIL	≈ 7¢/FT^2	AVAILABLE, DU PONT
b. TEDLAR 400 BG 20 SE, 4 MILS	≈ 30¢/FT^2	

Other Candidate Encapsulation Materials

1. Structural panels
- **a. Tempered, low-iron, soda lime float glass (≈ 75 ¢/ft^2, 1/8 in. thick)**
- **b. Cold-rolled mild steel (≈ 0.8 ¢/ft^2 · mil, 8-mils minimum rqmt)**
- **c. Wood hardboards (≈ 13 ¢/ft^2, 1/8 in. thick)**

2. Back covers (white-pigmented plastic films)
- **a. Tedlar 150 BL 30 WH, 1.5 mils thick (Du Pont)**
- **b. Tedlar 400 BS 20 WH, 4.0 mils thick (Du Pont)**
- **c. Scotchpar 10 CP White, 1.0 mils thick (3M Co.)**
- **d. Scotchpar 20 CP White, 2.0 mils thick (3M Co.)**
- **e. Korad 63000 White, 3.0 mils thick (Xcel Corp.)**

3. Edge seal and gasket
- **a. But, edge sealing tape (5354, 3M)**
- **b. EPDM gasket material (E-633, Pauling Rubber Co., Pauling, NY)**

4. Porous spacer
- **a. Craneglas non-woven E-Glass mats, Type 230**

Encapsulation Primers and Adhesives

PRIMERS

3) ELASTOMERS TO PLASTIC FILM SURFACES

COMPONENT	COMPOSITION
Z-6030 SILANE (DOW CORNING)	1 WT. %
Z-6040 SILANE (DOW CORNING)	1 WT. %
RESIMENE 740 (MONSANTO)	8 WT. %
ISOPROPYL ALCOHOL	90 WT. %

ADHESIVES

1) TEDLAR TO EVA/EMA, DU PONT ADHESIVE 68040

2) SCOTCHPAR TO WOOD, 3M ADHESIVE 4910

Adhesive Bond Strengths for EVA Bonded to Glass

		BOND STRENGTHS, LB/IN. OF WIDTH		
MATERIALS	PEROXIDE	CONTROL	2 WK IMMERSION	2 HOURS BOILING WATER
SUNADEX GLASS	L-101	34.8	30.0	32.3
WINDOW GLASS	L-101	39.6	37.9	27.1
WINDOW GLASS (SELF-PRIMING EVA)	L-101	35.4	41.9	COHESIVE
SUNADEX GLASS	L-TBEC	51.3	32.9	33.3

Adhesion Experiment Using TBEC-Cured EVA Mechanical Test Specimens Filled With 30% by Volume Glass Beads

EFFECT OF HYDROLYTIC AGING IN WATER AT 85°C						
SAMPLE AND PROPERTIES	IMMERSION TIME					
	CONTROL	24 HRS	96 HRS	192 HRS	360 HRS	528 HRS
UNFILLED EVA						
ELONGATION	575%	563	565	560	580	540
TENSILE	3,630 psi	2,259	2,709	2,577	2,650	2,460
MODULUS	755 psi	1,000	1,040	801	874	729
FILLED EVA						
ELONGATION	262%	270	280	190	205	120
TENSILE	980 psi	1,119	1,160	847	1,028	1,333
MODULUS	1,800 psi	1,900	2,200	610	1,900	2,800

Electrical Insulation: ac and dc Intrinsic Dielectric Strength

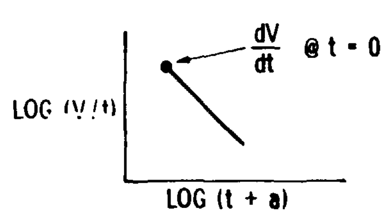
AC

- DATA CORRELATION

  $V_A = (V/t) = K(t + a)^{-n}$

- AC INTRINSIC DIELECTRIC STRENGTH

  $(dV/dt) = K(a)^{-n}$



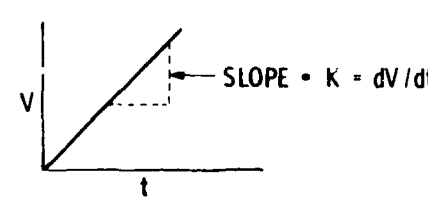
DC

- DATA CORRELATION

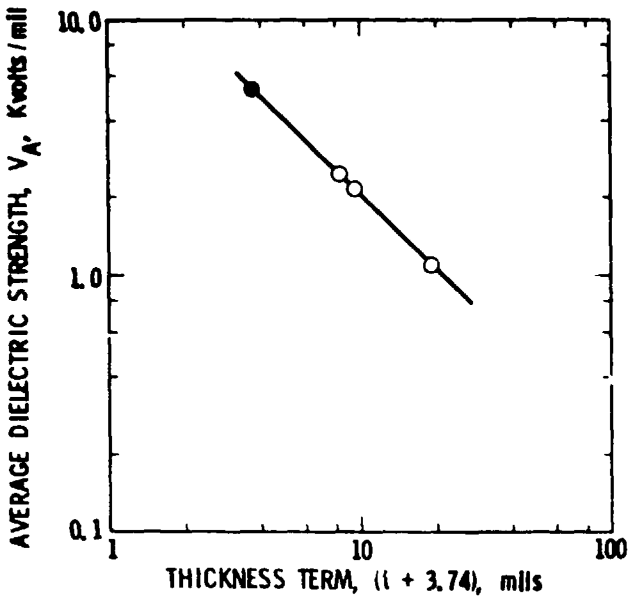
  $V = Kt$

- DC INTRINSIC DIELECTRIC STRENGTH

  $(dV/dt) = (V/t) = K$



Ac Dielectric Strength of A-9918 EVA



THICKNESS t, mils	AC BREAKDOWN VOLTAGE, KV	AVERAGE DIELECTRIC STRENGTH, V_A = V/t, KV/mil
4.7	11.7	2.49
6.0	13.0	2.17
15.7	17.6	1.12

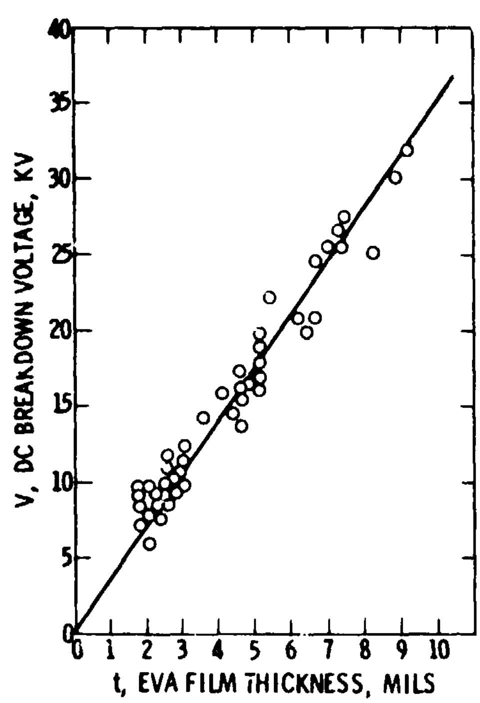
DATA CORRELATION

$V_A = 19173\,(t + 3.74)^{-0.96}$

AC INTRINSIC DIELECTRIC STRENGTH

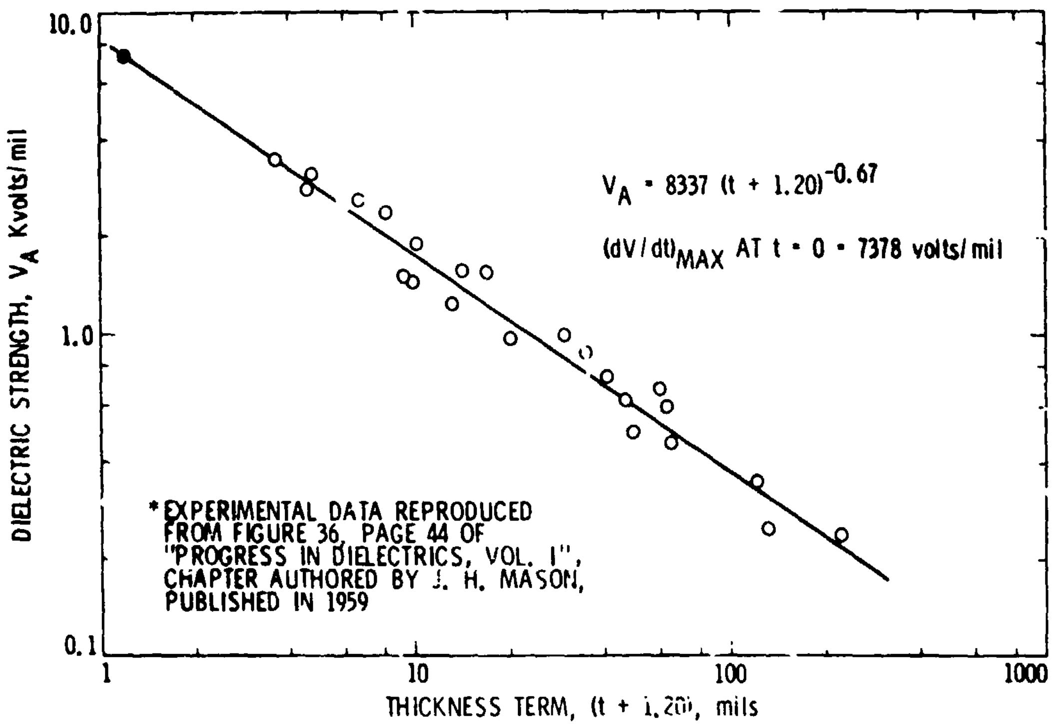
$\left(\frac{dV}{dt}\right) = 5404$ VOLTS/MIL @ t = 0

Dc Dielectric Strength of A-9918 EVA

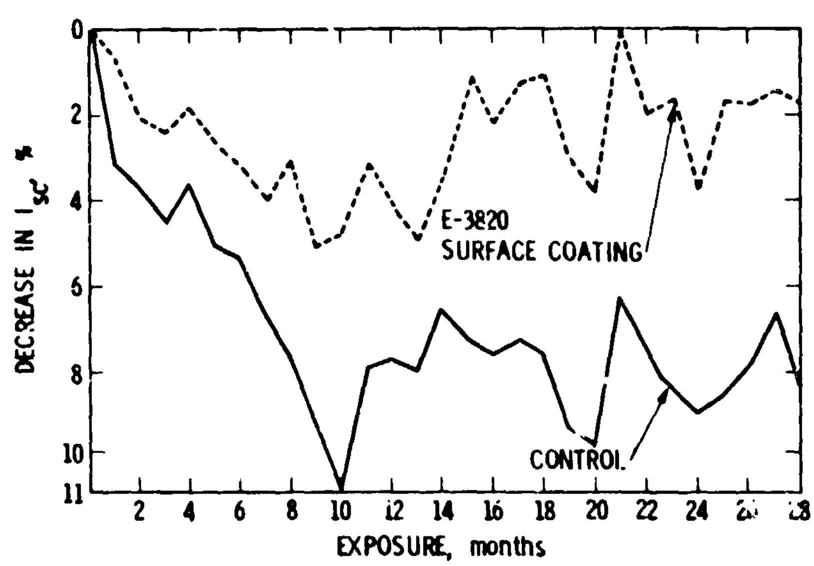


SLOPE = dV/dt = 3650 VOLTS/MIL

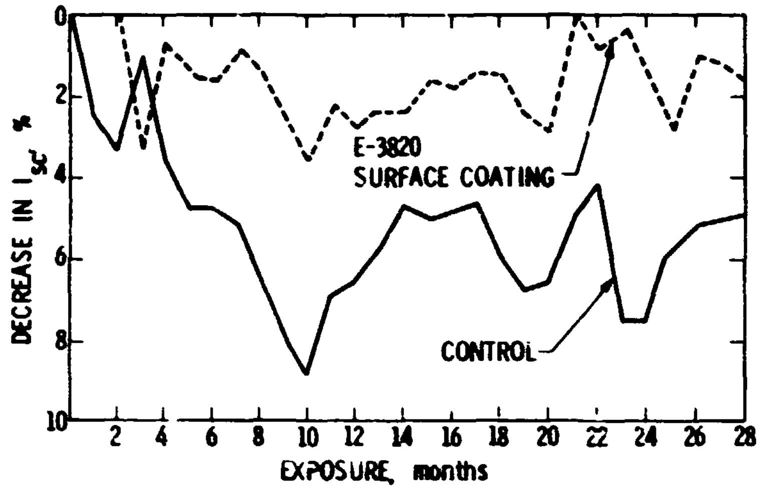
Dielectric Strength of Polyethylene*



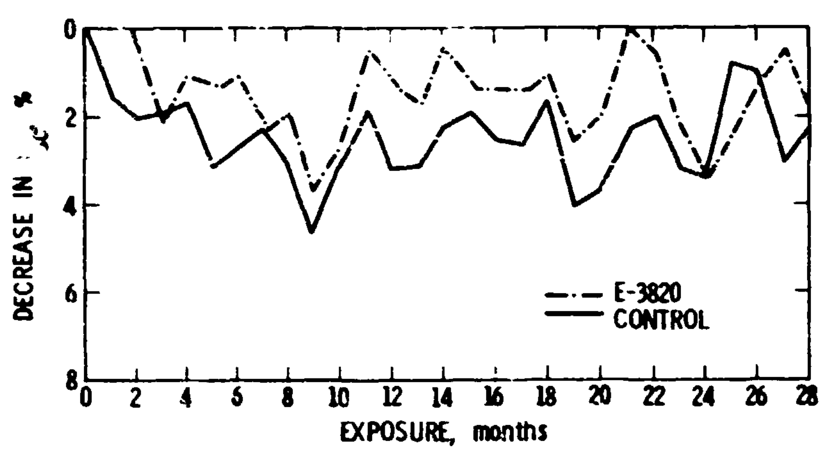
Outdoor Soiling Behavior of Acrylar X-22417 Plastic Film With & Without Fluorocarbon Antisoiling Coating



Outdoor Soiling Behavior of Tedlar 100BG30UT Plastic Film With & Without Fluorocarbon Antisoiling Coating



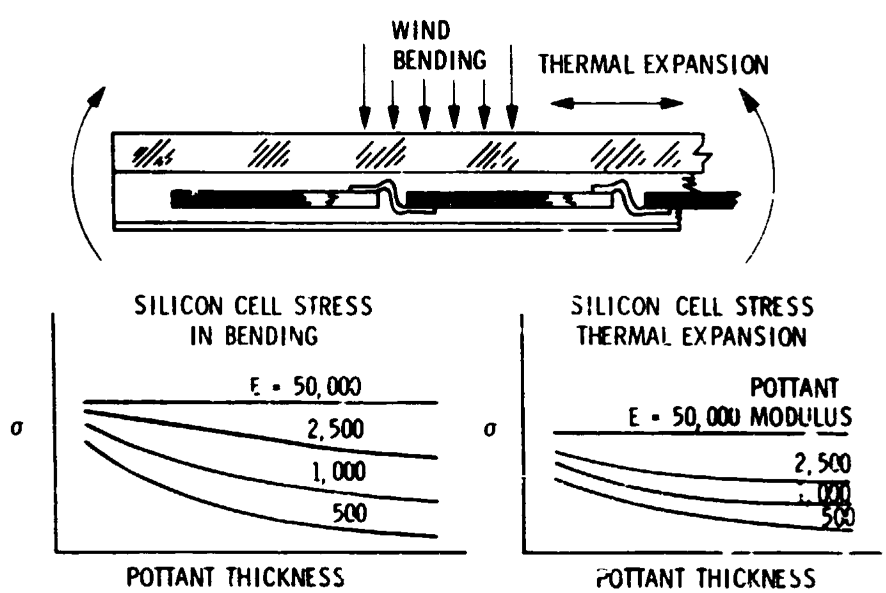
Outdoor Soiling Behavior of Glass With & Without Fluorocarbon Antisoiling Coating



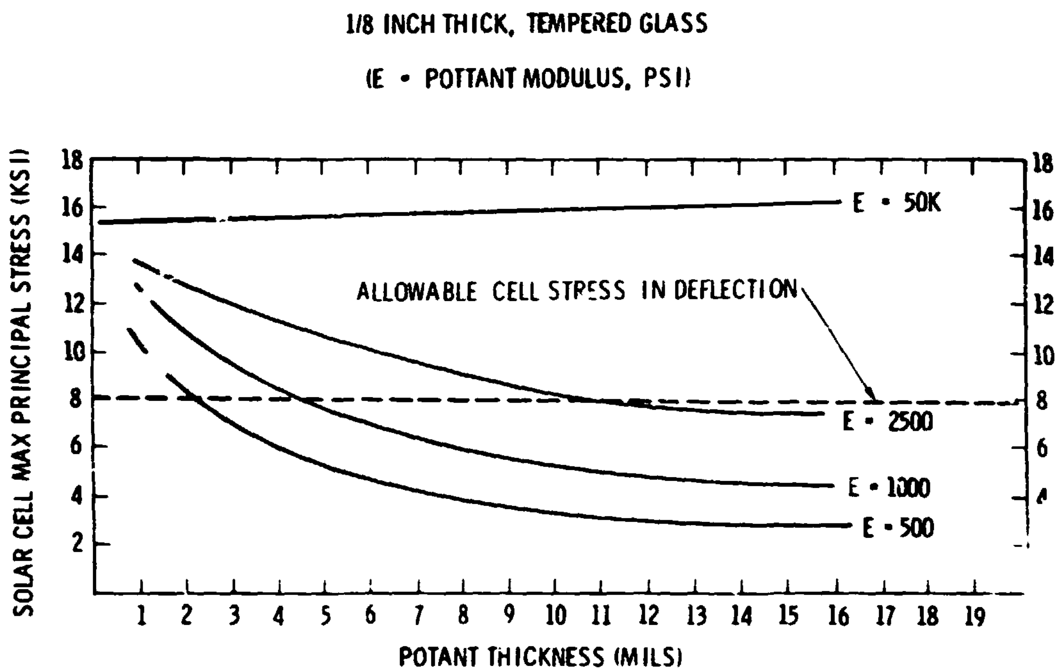
Time-Averaged Optical Losses After 28 Months of Outdoor Soiling in Enfield, CT

MATERIALS	TIME-AVERAGED OPTICAL LOSSES, %
GLASS	
CONTROL	2.65
WITH E-3820	1.55
WITH L-1668	1.59
TEDLAR	
CONTROL	5.38
WITH E-3820	1.70
WITH L-1668	4.43
ACRYLAR	
CONTROL	7.20
WITH E-3820	2.59
WITH L-1668	4.21

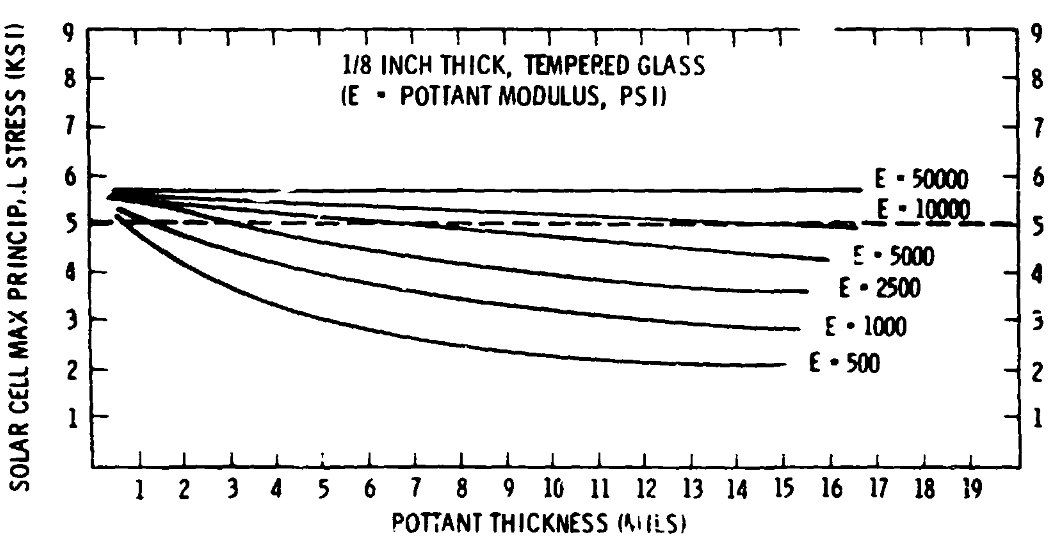
Encapsulant Design Analysis



Deflection Analysis: Glass Superstrate Design

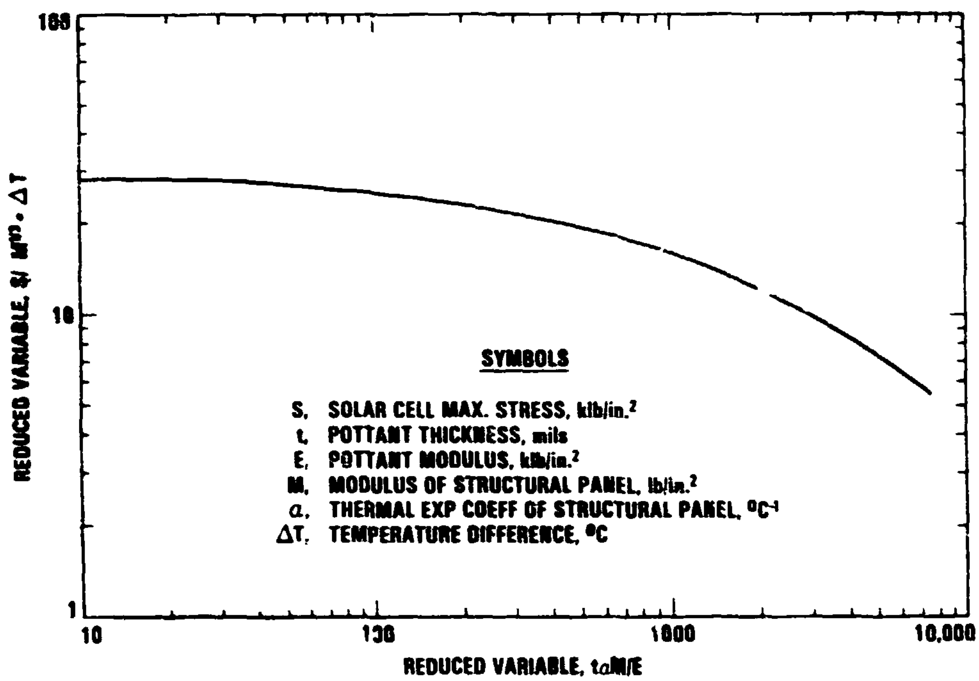


Thermal Stress Analysis (ΔT = 100°C): Glass Superstrate Design



DOTTED LINE - ALLOWABLE CELL STRESS IN TENSION

Master Curve for Thermal Stress Analysis



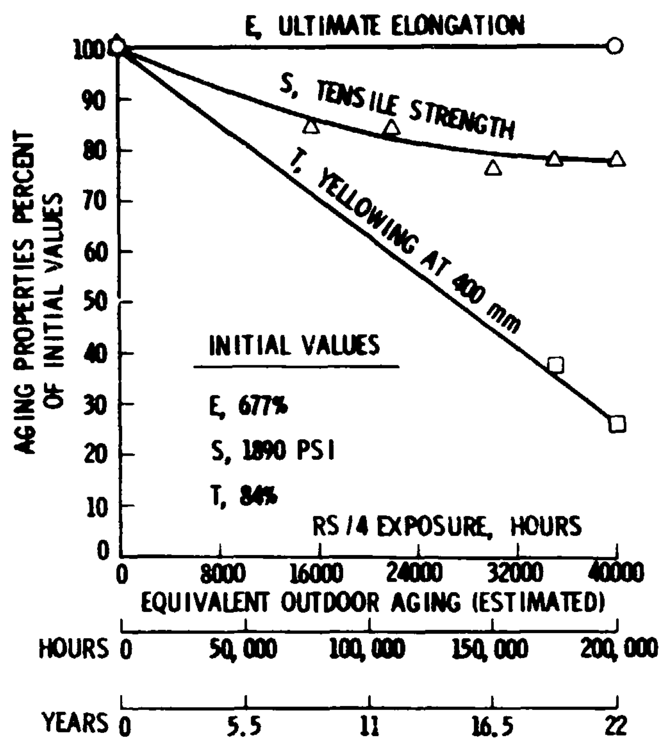
Life Assessment Program

1. DEVELOP PREDICTIVE AGING MODELS
   a. CONNECT CHANGE AND RATES-OF-CHANGE IN ENCAPSULATION MATERIAL PROPERTIES TO MODULE PERFORMANCE AND LIFE

2. ACCELERATED AGING METHODS
   a. AIR OVENS
   b. RS/4 SUN LAMPS (1.4 SUNS UV INTENSITY AT 50°C AND 85°C)
   c. CONTROLLED-ENVIRONMENTAL REACTORS (6 SUNS UV INTENSITY, ADJUSTABLE SAMPLE TEMPERATURE AND WATER-SPRAY CYCLE)
   d. OUTDOOR HEATED AGING RACKS (EXPOSURE OF MATERIALS AND MODULES TO NATURAL AGING ENVIRONMENT AT ADJUSTABLE ELEVATED TEMPERATURES)

3. MATERIAL TECHNOLOGIES
   a. CHEMICALLY ATTACHABLE UV ABSORBERS
   b. CHEMICALLY IN-SITU UV ABSORBERS
   c. POLYMERIC UV ABSORBERS

Aging of A-9918 EVA in RS/4 Sun Chambers at 50°C



Summary of EVA Aging at 50°C

EXPERIMENTAL

WEATHERING ADDITIVES	UV-SCREENING FILM OVERLAY	AGING REMARKS
NO	NO	YELLOWED AND DEGRADED WITHIN 1000 HOURS
NO	YES	NO YELLOWING OR DEGRADATION UP TO 20,000 HOURS
YES	NO	NO DEGRADATION, BUT GRADUAL YELLOWING UP TO 40,000 HOURS

FINDINGS

1) EVA APPEARS NOT TO UNDERGO THERMAL OXIDATION AT TEMPERATURES UP TO 50°C

2) EVA DOES UNDERGO PHOTO-OXIDATION

CONCLUSION

LIFE OF EVA POTTANT IN OUTDOOR SERVICE AT 50°C (OR LESS) RELATED TO PERMANENCE OF THE MODULE'S UV PROTECTION SYSTEM

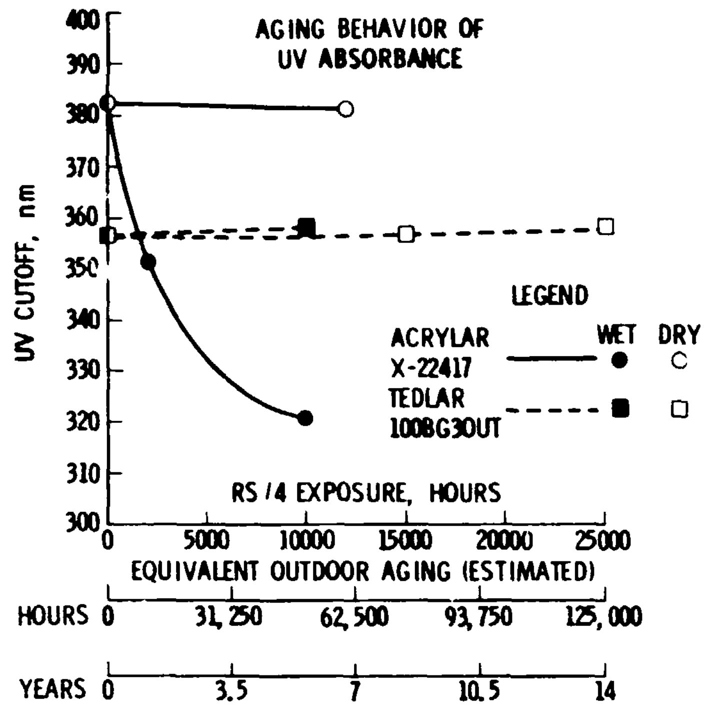
Limitations Identified for the Current Version of A-9918 EVA

MATERIALS	PROBLEM	CORRECTION
1) PEROXIDE CURING AGENT a) LUPERSOL 101	• EVA IMMISICIBILITY • RAPID PHYSICAL LOSS • POOR STORAGE LIFE • EVA CURE PROBLEMS	REPLACE WITH LUPERSOL TBEC; IMPROVED BLENDING, STORAGE, CURE
2) WEATHERING STABILIZERS a) TINUVIN 770 b) CYASORB UV-531	• LOW MOLECULAR WEIGHT • RAPID PHYSICAL DEPLETION • GRADUAL LOSS OF EVA WEATHERING PROTECTION	REPLACE WITH NON-FUGITIVE WEATHERING STABILIZERS

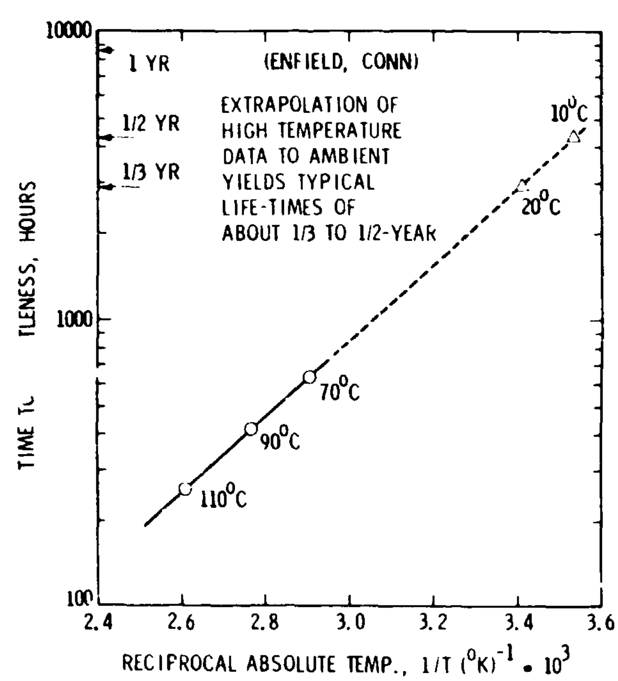
Advanced EVA Formulation (Experimental): Springborn No. 18170

COMPONENT	FUNCTION	REMARK
• ELVAX 150	EVA RESIN	SAME AS A-9918
• TBEC	CURING AGENT	FASTER, LOWER TEMPERATURE CURING, IMPRCVED STORAGE LIFE
• UV-2098	UV-SCREEN	CHEMICALLY ATTACHABLE, NON-FUGITIVE
• UV-3346	HINDERED AMINE LIGHT STABILIZER (HALS)	POLYMERIC, NON-FUGITIVE

Aging of Commercial UV Screening Films in RS/4 Sun Chambers at 50°C



Natural Outdoor Aging of Polypropylene on the Outdoor Heating Racks at 70°C, 90°C and 110°C



Accelerated Aging Program: Quantifiable Aging Properties

PROPERTY	MEASURABLE
1) OPTICAL	• UV, VISIBLE, IR SPECTRA • % TRANSMISSION AT 400 nm
2) MECHANICAL	• MODULUS, STRENGTH, ELONGATION
3) ELECTRICAL	• DC INTRINSIC DIELECTRIC STRENGTH
4) CHEMICAL	• ADDITIVE CONCENTRATIONS • RESIN CHEMISTRY/COMPOSITION
5) ADHESION	• INTERFACE FTIR SPECTROSCOPY • MECHANICAL PROPERTIES OF GLASS-BEAD FILLED SPECIMENS

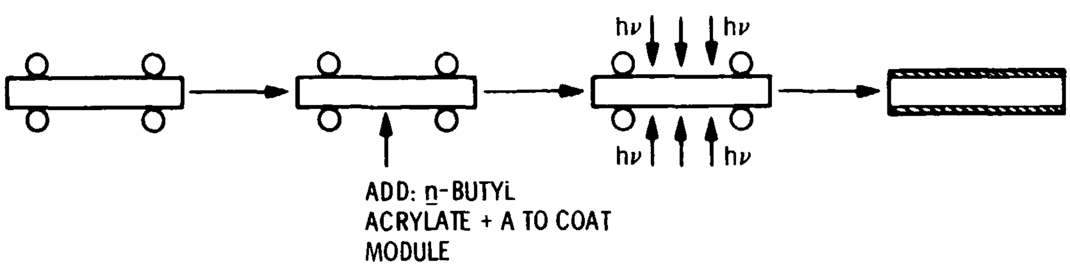
New Concepts for Thin-Film Silicon Cell Encapsulation

- DEVELOPMENT OF CONFORMAL POLYMERIC LAYERS ON THIN FILM SILICON CELLS USING PHOTOPOLYMERIZATION TECHNIQUES
  - WHAT IS PHOTOPOLYMERIZATION?
    - MONOMER + CATALYST $\xrightarrow{h\nu}$ POLYMER
  - ADVANTAGES
    - ROOM TEMPERATURE PROCESSING
    - EXTREMELY RAPID PROCESSING (1 - 10 sec)
    - CAN HANDLE VINYLS, ACRYLICS, SILICONES, SILICONE-ACRYLICS, FLUOROPOLYMERS, EPOXIES, URETHANES, POLYESTERS – A WIDE VARIETY OF POLYMERS
    - IN SITU PROCESSING CAN LEAD TO ENCAPSULATION IN ONE STEP

Current Industrial Applications of Photopolymerization

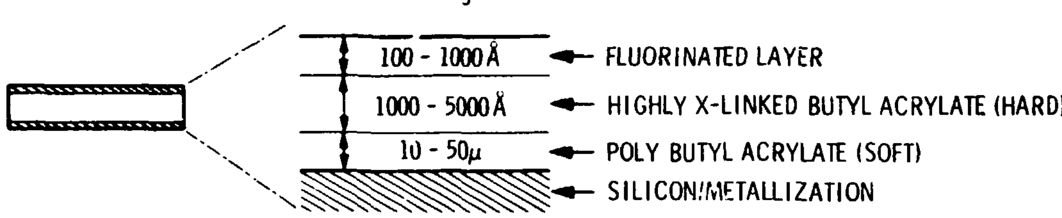
- ENCAPSULATION OF OPTICAL FIBERS
- DEPOSITION OF RESIST FILM ON MICROCIRCUITS

Example of an Encapsulation Scheme Using Photopolymerization



A: $CF_3(CF_2)_9\,COON[(CH_2)_3\,COOC(CH_3)=CH_2]_2$

A: PERFLUORINATED ACRYLIC X LINKING AGENT (HIGH T_g) – IMMISCIBLE WITH NBA



Potential Reliability Issues

- EFFECT OF STABILIZING ADDITIVES ON THE PHOTOPOLYMERIZATION PROCESSING CONDITIONS
- LONG TERM STABILITY OF THE COATING AND INTERFACES – EFFECTIVENESS OF ADDITIVES IN ULTRATHIN LAYERS
- ROLE OF THE SURFACE FLUORINATED LAYER AS AN OXIDATION INHIBITOR
- ANTISOILING CHARACTERISTICS OF THE SURFACE LAYER