5101-216
Flat-Plate
Solar Array Project

DOE/JPL-1012-77
Distribution Category UC-63b

Photovoltaic Module Encapsulation Design and Materials Selection, Volume I (Abridged)

E. Cuddihy

(NASA-CR-169372) PHOTOVOLTAIC MODULE ENCAPSULATION DESIGN AND MATERIALS SELECTION, VOLUME 1, ABRIDGED (Jet Propulsion Lab.) 40 p HC A03/MF A01 N83-10553
CSCL 10A G3/44 Unclas 35523

September 1, 1982

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
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The JPL Flat-Plate Solar Array Project is sponsored by the U.S. Department of Energy and is part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of cost-competitive solar arrays.

This publication reports on work done under NASA Task RD-152, Amendment 66, DOE/NASA IAA No. DE-AI01-76ET20356.

ABSTRACT

Photovoltaic Module Encapsulation Design and Materials Selection, Volume I, JPL Document No. 5101-177, JPL Publication 81-102, DOE/JPL-1012-60, Jet Propulsion Laboratory, Pasadena, California, June 1, 1982, (Reference 1), describes in detail the functional requirements and the status of candidate material systems and processes for photovoltaic modules. This document is a summary version of Volume I, presenting the basic encapsulation systems, their purposes and requirements, and the characteristics of the most promising candidate systems and materials, as identified and evaluated by the Flat-Plate Solar Array Project.

In this summary version considerable detail and much supporting and experimental information has necessarily been omitted. A reader interested in references and literature citations, and in more detailed information on specific topics, should consult Reference 1.

PREFACE

Encapsulation-material system requirements, material-selection criteria, and the status and properties of encapsulation materials and processes available to the module manufacturer are presented in detail in Photovoltaic Module Encapsulation and Materials Selection, Volume I (Reference 1). Technical and economic goals established for photovoltaic (PV) modules and encapsulation systems and their status are described for material suppliers to assist them in assessing the suitability of materials in their product lines and the potential of new-material products.

A comprehensive discussion of available encapsulation technology and data is presented therein, to facilitate design and material selection for silicon flat-plate PV modules, using the best materials available and processes optimized for specific power applications and geographic sites.

Section II of Reference 1 provides a basis for specifying the operational and environmental loads that encapsulation material systems must resist. Potential deployment sites for which cost effectiveness may be achieved at a module price much greater than $\$0.70/W_p$ are also considered; data on higher-cost encapsulant materials and processes that may be in use and other material candidates that may be justified for special application are discussed.

Section III of Reference 1 describes encapsulation-system functional requirements and candidate design concepts and materials that have been identified and analyzed as having the best potential to meet the cost and performance goals for the FSA Program. Sections IV, V, and VI of Reference 1 present the available data on encapsulant material properties, fabrication processing and evolving trends relative to module life and durability characteristics.

Annual supplements to Volume I, reporting in detail on information accumulated within the reporting year, are planned.

ACKNOWLEDGMENT

The author gratefully acknowledges the assistance and encouragement of the many members of the Environmental Isolation Task of the Flat-Plate Solar Array Project for their contributions to this report.

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SECTION I

INTRODUCTION

The Jet Propulsion Laboratory manages the Flat-Plate Solar Array Project (FSA) for the U.S. Department of Energy. The project goals are to develop technologies that would create an industrial capability of producing solar cell modules for terrestrial power at a capital cost of 70¢/W_p (in 1980 dollars) and with a minimum service lifetime of 20 years. Assuming a module efficiency of 10%, which is essentially 100 W/m^2 at solar meridian, the capital cost of the modules can be alternatively quoted as \$70.00/m^2. Out of this cost goal, \$14.00/m^2 is allocated for encapsulation materials, which include the cost of a structural panel, edge seals and gaskets. At project inception in 1975, the cumulative cost of encapsulation materials in popular use, such as RTV silicones, aluminum panels, etc., greatly exceeded \$14.00/m^2. Accordingly, FSA seeks to identify and/or develop, as necessary, new materials and new material technologies to achieve the cost and life goals.

To accomplish these goals six technical activities were established:

(1) Generation of specifications and functional requirements for encapsulation materials.

(2) Identification or development of lowest-costing materials that satisfy the specifications and functional requirements.

(3) Engineering requirements of an encapsulation system to provide guidelines for minimum material usage.

(4) Identification of life and/or weathering deficiencies in the low-cost materials.

(5) Generation of necessary design approaches or material modifications to enhance life or weathering stability.

(6) Life prediction methodologies for encapsulation systems.

This document summarizes the first three task activities, including the inventory of encapsulation materials meeting the FSA cost goals, and is an abridgment of Photovoltaic Module Encapsulation Design and Materials Selection: Volume I (Reference 1). Unless otherwise noted, all material costs are quoted herein in 1980 dollars.

A companion document titled Photothermal Characterization of Encapsulant Materials for Photovoltaic Modules (Reference 2) describes the current status and findings of the other three task activities (4, 5 and 6 above).

SECTION II

ENCAPSULATION REQUIREMENTS AND MATERIALS

Photovoltaic modules contain strings of electrically interconnected solar cells capable of producing practical quantities of electricity when illuminated with sunlight. Silicon solar cells are fragile and are especially sensitive to brittle failure in tension and bending. The electrically conductive metallization materials (functioning as grids, interconnects, bus bars, and terminals) must be protected from corrosion or other deteriorating interaction with the terrestrial environment. In short, the silicon solar cells must be mechanically supported, and the electrically conductive circuit materials must be isolated from environmental exposure.

Encapsulation materials are defined as all construction materials (excluding cells and electrical conductors) required in a PV module to provide mechanical support and environmental isolation. Early FSA encapsulation efforts to identify a single material that could satisfy all of the encapsulation requirements and needs were unsuccessful. The understanding evolved that more than one material would have to be assembled in a composite package to fabricate an encapsulated module.

After an examination of all commercial and experimental flat-plate module encapsulation designs, it was found that these designs could be separated into two basic classes (Figure 1). These are designated as substrate-bonded and superstrate-bonded designs, referring to the method by which the solar cells are mechanically supported. In the substrate design, the cells are bonded to a structural substrate panel; in the superstrate design the cells are bonded to a transparent structural superstrate.

From these two design options, nine basic encapsulation construction elements can be identified. These are illustrated in Figure 2, with their designations and encapsulation functions. Fabricated modules need not use all nine of these construction elements, but combinations of these basic elements are incorporated in most module designs. Cross-section views of representative designs are illustrated in Figure 3, and typical industrial designs are shown in Figure 4.

In the early 1970s the first versions of terrestrial photovoltaic modules were generally substrate designs, using silicone rubber as the pottant. The substrates were typically aluminum, G-10 epoxy boards, or glass-fiber-reinforced polyester boards. Some encapsulation problems with these early-version modules were delamination of silicone from the substrates, heavy accumulation of light-obscuring soil on the soft silicone surfaces, and hail damage to solar cells. Aluminum pans were gradually phased out because of a combination of high cost and large thermal expansion mismatch with silicon cells, causing solar-cell breakage. Delamination problems gradually diminished with proper use of primers and adhesives.

To counter soil accumulation and hail damage, manufacturers began to switch from the substrate design in favor of a glass-superstrate design. In parallel with this trend, polyvinyl butyral (PVB) was also introduced industrially as a pottant, requiring a lamination processs for module fabrication.

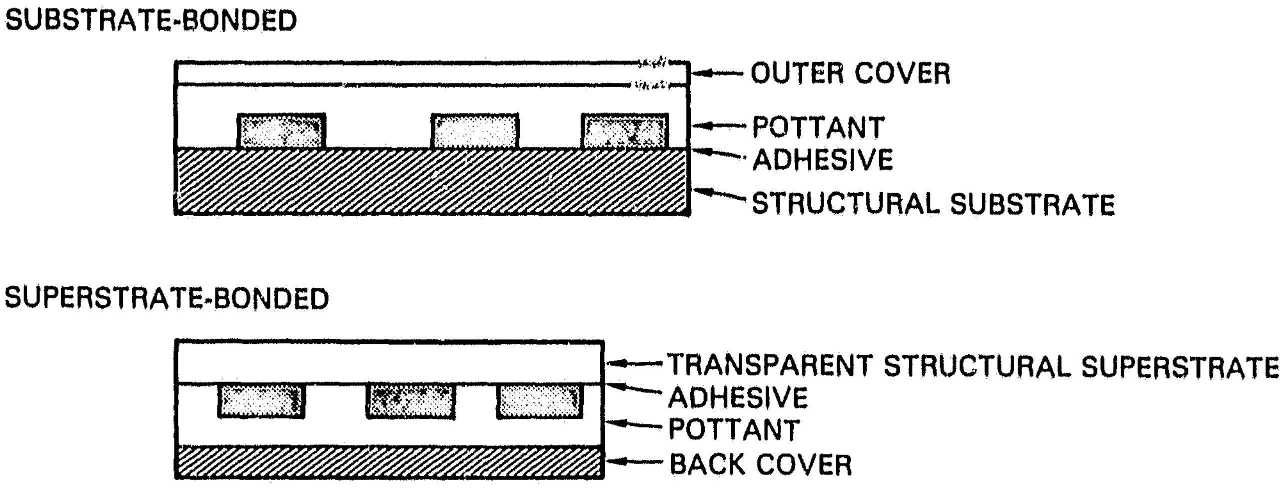
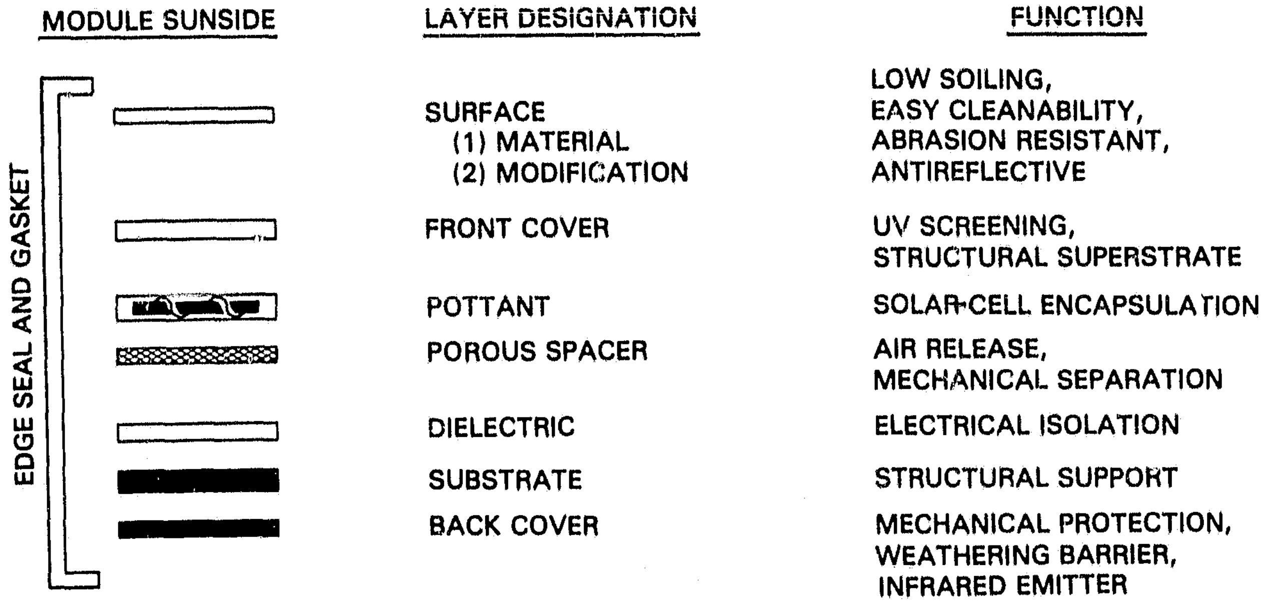


Figure 1. Flat-Plate Module Design Classifications



LAYER DESIGNATION	FUNCTION
SURFACE (1) MATERIAL (2) MODIFICATION	LOW SOILING, EASY CLEANABILITY, ABRASION RESISTANT, ANTIREFLECTIVE
FRONT COVER	UV SCREENING, STRUCTURAL SUPERSTRATE
POTTANT	SOLAR-CELL ENCAPSULATION
POROUS SPACER	AIR RELEASE, MECHANICAL SEPARATION
DIELECTRIC	ELECTRICAL ISOLATION
SUBSTRATE	STRUCTURAL SUPPORT
BACK COVER	MECHANICAL PROTECTION, WEATHERING BARRIER, INFRARED EMITTER

PLUS NECESSARY PRIMER-ADHESIVES

Figure 2. Encapsulation Materials: Module Construction Elements

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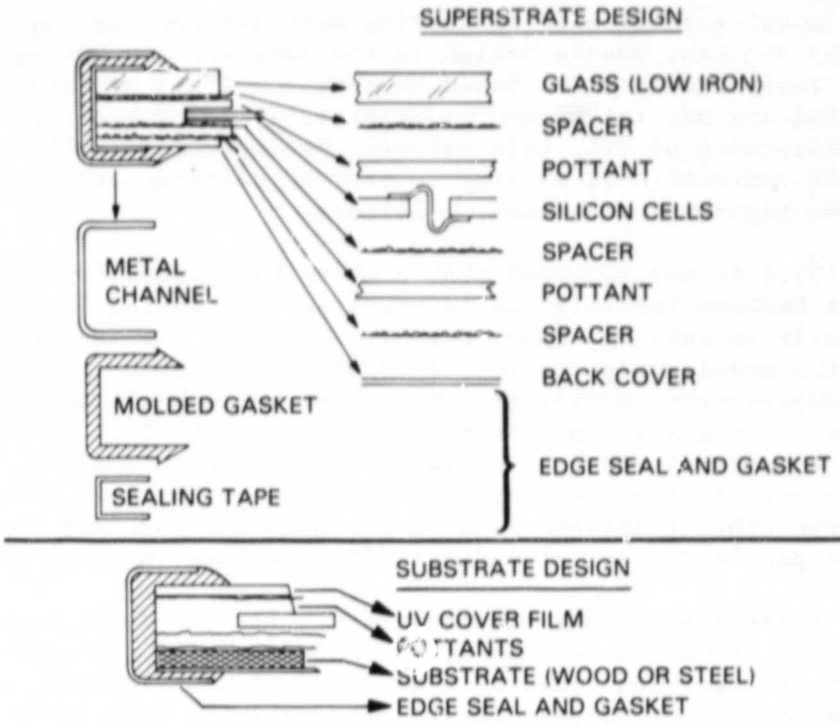

Figure 3. Cross-Sectional Views of Representative Superstrate and Substrate Designs

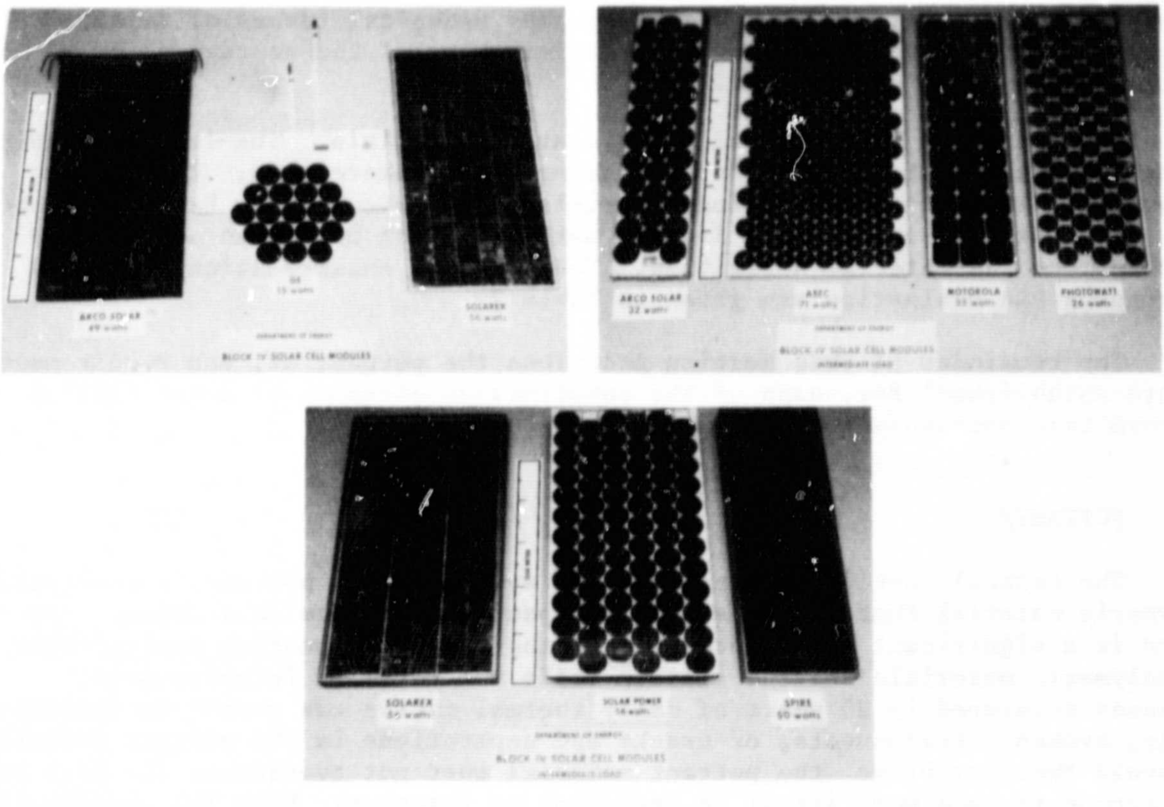

Figure 4. Typical Industrial Designs

Glass-superstrate modules fabricated by casting with silicone and by lamination with PVB became the dominant module design in the late 1970s. During 1977 and 1978 a lower-cost lamination pottant based on ethylene vinyl acetate (EVA) was developed within FSA and was introduced experimentally to PV manufacturers. With industrial acceptance of EVA, this material became commercially available in April 1981. FSA activities to develop lower-cost casting pottants, as alternatives to the high-cost silicones, continues.

During the 1970s it was observed that a white background (see Figure 4) in the open spaces between the solar cells resulted in internal light reflection and consequently in enhanced power output. Further, a white surface on the back side of the module helps to reduce module temperatures. Today's commercial glass superstrate modules generally have white backgrounds and white back surfaces. In glass superstrate designs, a white back-cover film functions as both background and back surface. In substrate designs, the front and back surfaces of the substrate panel are coated with white materials that generally serve other functions also, e.g., moisture barriers in humidity-sensitive panels or corrosion-protection coatings in metal panels.

In general, glass-superstrate encapsulation will cost more than substrate encapsulation, primarily because of the difference in the cost of glass compared with that of lower-cost substrate panels such as hardboards and mild steel. Today, the cost of glass superstrate encapsulation is a small percentage of the total module cost because of the much higher cost of the silicon solar cells. As the cost of silicon comes down in the future and cells become thinner (therefore using less silicon), the cost of encapsulation as a percentage of total module cost will increase. Therefore, substrate encapsulation designs can result in substantial cost reductions for future generations of PV modules. For these low-cost designs, the key technical issues of delamination, hail resistance, soiling, and minimization of the weather-aging of low-cost materials must be resolved.

Table 1 is an inventory of encapsulation materials. The left-hand column lists materials that have been or are being used commercially. The middle column is a list of encapsulation materials that are currently being evaluated, and the right-hand column is a list of materials that have been assesed and deleted from FSA material activities. The costs of encapsulation materials undergoing FSA evaluation are given in Table 2.

The remainder of this section describes the purpose of, and requirements (where established) for, each of the construction elements of a terrestrial photovoltaic encapsulation system.

A. POTTANTS

The central core of an encapsulation system is the pottant, a transparent polymeric material that is the actual encapsulation medium in a module. As there is a significant difference between the thermal-expansion coefficients of polymeric materials and the silicon cells and metallic interconnects, stresses developed in 20 years of daily thermal cycles can result in fractured cells, broken interconnects, or cracks and separations in the pottant material. To avoid these problems, the pottant material must not overstress the cell and interconnects, and must itself be resistant to fracture. From the results of

Table 1. Inventory of Encapsulation Materials

	Commercial Materials	Materials Being Evaluated	Materials Assessed and Deleted from FSA Activities
Front Covers	Low-iron tempered soda-lime glass Borosilicate glass Plexiglas, Lucite acrylic sheet Lexan (polycarbonate) Tedlar 400 XRB 160 SE film Llumar weatherized polyester film Korad 212 acrylic film	X-22416 acrylic film (3M) X-22417 acrylic film (3M) Tedlar 100 BG 30 UT (Du Pont)	Korad 212 acrylic film Silicone/acrylic copolymer film
Pottants	Polyvinyl butyral (PVB) Silicone rubber (RTV 615, Sylgard 184) Silicone gels Ethylene vinyl acetate (EVA)	Ethylene vinyl acetate Ethylene methyl acrylate Poly-n-butyl acrylate Aliphatic polyether urethanes	Polyvinyl chloride plastisol Ethylene propylene rubber Q1-2577 silicone resin Silicone/acrylic copolymer liquid Ionomer (Du Pont)
Sub-strates	Glass, tempered or annealed Lexan (polycarbonate) Porcelainized steel Glass-fiber-reinforced polyester Pressed paper board (shingle design) Aluminum NEMA-G10 epoxy board	Hardboards (wood) Mild steel Glass-reinforced concrete	Strandboards Galvanized steel Kraft paper honeycombs Paper boards Plywood
Back Covers	Mylar (clear) White-pigmented Tedlar Aluminum foil/Tedlar Tedlar/aluminum foil/Tedlar Tedlar/stainless-steel foil/Tedlar Black polyethylene	Scotchpar-20C-white polyester (3M) White polyethylene White Korad (XCEL) Polyester/aluminum foil/polyester White melamine formaldehydes for wood Corrosion-prevention coatings for mild steel White pigmented pottants	Stainless-steel foil

Table 1. Inventory of Encapsulation Materials (Cont'd)

	Commercial Materials	Materials Being Evaluated	Materials Assessed and Deleted from FSA Activities
Spacer	Craneglas non-woven glass mats	Craneglas non-woven glass mats	Non-woven polyester glass mats Paper tissue
Dielectric Films	White Korad acrylic film (XCEL)	White Korad acrylic (XCEL) White polyethylene Scotchpar-20CP-white polyester (3M)	
Edge Gaskets	Silicone rubber Neoprene	Ethylene propylene rubber (EPDM, E-633, Pauling)	
Edge Seals	Silicones Polysulfides Butyls	Butyl wrap-around tape (5354, 3M)	
Edge Frames	Aluminum extrusion Cor-Ten steel extrusion Pultrusion fiber-reinforced polyester Rovel (Uniroyal)		
Surface-Dirt Cover	Q1-2577 silicone resin (Dow Corning)	Fluorinated silane (L-1668, 3M) Fluorinated acrylics (FC-721, FC-723, 3M) Perfluorodecanoic acid with Dow Corning E-3820 chemical coupling primer	

Table 2. Costs[a] of Current Encapsulation Materials Undergoing FSA Evaluation

Materials	Cost
Low-Soiling Treatments	
Fluorinated silane (L-1668, 3M)	$\$0.01/\mathrm{ft}^2$ (sub-mil thickness)
Fluorinated acrylics (FC-721, FC-723, 3M)	$\$0.01/\mathrm{ft}^2$ (sub-mil thickness)
Perfluorodecanoic acid with E-3820 chemical coupling primer (Dow Corning)	$\$0.01/\mathrm{ft}^2$ (sub-mil thickness)
Glass (for superstrate design)	
Low-iron tempered soda-lime glass (e.g., Sunadex)	$\$0.55$ to $\$0.85/\mathrm{ft}^2$ (1/8-in. thick)
UV-Screening Plastic Film Front Covers (for substrate design)	
Tedlar 100-BG-30-UT (1-mil fluorocarbon film, Du Pont)	$\$0.079/\mathrm{ft}^2$
Acrylar X-22416 (2-mil acrylic film, 3M)	$\$0.048/\mathrm{ft}^2$
Acrylar X-22417 (3-mil acrylic film, 3M)	$\$0.067/\mathrm{ft}^2$
Pottants[b]	
Ethylene vinyl acetate (A-9918, Springborn; Rowland/Du Pont)	$\$0.95/\mathrm{lb}$; $\$0.0048/\mathrm{ft}^2$-mil
Ethylene methyl acrylate (A-11877, Springborn)	$\$0.95/\mathrm{lb}$; $\$0.0048/\mathrm{ft}^2$-mil
Poly-n-butyl acrylate (A-13870, Springborn)	$\$0.85/\mathrm{lb}$; $\$0.0045/\mathrm{ft}^2$-mil
Aliphatic polyether urethane (Z-2591, Development Associates)	$\$3.00/\mathrm{lb}$; $\$0.0152/\mathrm{ft}^2$-mil
Porous Spacer	
Non-woven E-glass mats (Craneglas)	$\$0.0078/\mathrm{ft}^2$ (5 mils thick)
Dielectric Films (White-Pigmented)	
Scotchpar 10-CP-White (1-mil polyester film, 3M)	$\$0.020/\mathrm{ft}^2$
Scotchpar 20-CP-White (2-mil polyester film, 3M)	$\$0.040/\mathrm{ft}^2$
Tedlar 150-BL-30-WH (1.5-mil fluorocarbon film, Du Pont)	$\$0.075/\mathrm{ft}^2$
Korad 63000 (3-mil acrylic film, XCEL)	$\$0.045/\mathrm{ft}^2$

Table 2. Costs[a] of Current Encapsulation Materials Undergoing FSA Evaluation (Cont'd)

Materials	Cost
Substrates	
Mild steel (various suppliers)	$0.0075/ft^2$-mil
Hardboard (Super-Dorlux, Masonite; Duron, U.S. Gypsum)	$0.13 to $0.15/ft^2$ (1/8-in. thick)
Back Covers (White Pigments)	
Scotchpar 10-CP-White (1-mil polyester film, 3M)	$0.02/ft^2$
Scotchpar 20-CP-White (2-mil polyester film, 3M)	$0.04/ft^2$
Tedlar 150-BL-30-WH (1.5-mil fluorocarbon film, Du Pont)	$0.075/ft^2$
Tedlar 400-BS-20-WH (4-mil fluorocarbon film, Du Pont)	$0.284/ft^2$
Korad 63000 White (3-mil acrylic film, XCEL)	$0.045/ft^2$
Edge Gasket[c]	
Ethylene-propylene rubber (EDPM, E-633, Pauling Rubber Co.)	$0.33/linear ft
Edge Seal	
Butyl wrap-around tape (5354, 3M)	$0.02-$0.04/linear ft

[a] Unless otherwise indicated, prices are in 1980 dollars and are at lowest discounted levels associated with high-volume purchases.

[b] Currently, the lowest price for commercial EVA in 1982 dollars is $0.0135/ft^2$-mil, associated with present-day production levels. Costs quoted in this table for EVA, EMA, and PnBA are lowest estimates for high-volume production. The cost of $3.00/lb for polyurethane is a 1982 commercial price, expected to decrease if volume of use increases.

[c] EPDM gaskets experimentally made by Pauling for PV module evaluation are understandably high-priced, as quoted in this table. With increasing usage, the cost should drop. The cost of EPDM material in the gasket is estimated at $0.02/linear foot, thus indicating level of markup for low-volume production of a product that is now a specialty item.

theoretical analysis, experimental efforts and observations of the materials of choice used for pottants in commercial modules, the pottant must be a low-modulus, elastomeric material.

Also, these materials must be transparent, processible, commercially available, and should be inexpensive. In many cases, commercially available materials are not physically or chemically suitable for immediate encapsulation use, and therefore must also be amenable to low-cost modification. The pottant materials must have either inherent weatherability (retention of transparency and mechanical integrity under weather extremes) or have the potential for long life that can be provided by cost-effective protection incorporated into the material or the module design. Evolving specifications and requirements for compounded pottant materials are set forth in Table 3.

In a fabricated module, the pottant provides three critical functions for module life and reliability:

(1) Maximum optical transmission in the silicon solar cell operating wavelength range of 0.4 μm to 1.1 μm.

(2) Retention of a required level of electrical insulation to protect against electrical breakdown, arcing, etc., and the associated hazards of electrical fire and danger to human safety.

(3) The mechanical properties to maintain spatial containment of the solar cells and interconnects, and to resist mechanical creep. The level of mechanical properties also must not exceed values that would impose undue mechanical stresses on the solar cell.

When exposed to outdoor weathering, polymeric materials can experience degradation that could affect their optical, mechanical, and electrical insulation properties. Outdoors, polymeric materials can degrade from one or more of the following weathering actions:

(1) UV photooxidation.

(2) UV photolysis.

(3) Thermal oxidation.

(4) Hydrolysis.

At expected temperature levels in operating modules, 60°C in a rack-mounted array and possibly up to 80°C on a rooftop, three generic classes of transparent polymers are generally resistant to the above weathering actions: silicones, fluorocarbons, and polymethyl methacrylate (PMMA). Of these three, only silicone rubbers, which are expensive, have been available as low-modulus elastomers suitable for pottant application.

Other transparent, low-modulus elastomers such as PVB will in general experience some degree of weathering degradation. However, less weatherable and lower-costing materials can be considered for pottant application if the module design can provide the necessary degree of environmental protection. For example, a hermetic design, such as a glass superstrate with a metal-foil

Table 3. Evolving Specifications and Requirements for Compounded Pottant Materials

Description	Specification or Requirement
Glass transition temperature (T_g)	<-40°C
Total hemispherical light transmission through a 20-mil-thick film integrated over the wavelength range from 0.4 μm to 1.1 μm	>90% of incident
Hydrolysis	None at 80°C, 100% RH
Resistance to thermal oxidation (oven aging)	Stable up to 85°C
Mechanical creep	None at 90°C
Tensile modulus as measured by initial slope of stress-strain curve	<3000 lb/in.^{2} at 25°C
Fabrication compatibility	Can be fabricated into modules using industrial state-of-the-art lamination or casting equipment
Fabrication temperature	≤170°C for either lamination or liquid pottant systems
Fabrication pressure for lamination pottants	≤1 atm
Chemical inertness	No reaction with embedded copper coupons at 90°C
UV absorption degradation	None at wavelength >0.35 μm
Hazing or clouding	None at 80°C, 100% RH
Minimum thickness on either side of solar cells in fabricated modules	6 mils
Odor, human hazards (toxicity)	None

back cover and appropriate edge sealing, will essentially isolate the interior pottant from exposure to oxygen and water vapor, with the glass itself providing a level of UV shielding.

The situation is different, however, with a substrate module, which will use a weatherable plastic-film front cover. Because all plastic films are permeable to oxygen and water vapor (the only difference is permeation rate), the underlying pottant will be exposed to oxygen and water vapor, and also to UV if the plastic film is non-UV-screening. Because isolation of the pottant from oxygen and water vapor is not practical in this design option, it becomes a requirement that the pottant be intrinsically resistant to hydrolysis and thermal oxidation, but sensitivity to UV is allowed if the weatherable front-cover plastic film can provide UV shielding.

Therefore, surveys were done to identify the lowest-cost transparent low-modulus elastomers with expected resistance to hydrolysis and thermal oxidation at temperatures up to 80°C, but these materials were allowed to be sensitive to UV deterioration. It was envisioned that if such a set of pottant candidates were selected on the basis of a less-protective substrate-module design, they would also be usable in a potentially more-protective glass-superstrate design. In addition to the foregoing requirement for candidate pottant selection, these materials must also be capable of being fabricated into modules by industrial methods. This requirement becomes important, as it is desirable to have industrial evaluation of the materials being developed, and thus the materials must be readily usable on commercial equipment. The two industrial fabrication techniques in common use are lamination and casting.

With all of these requirements, four pottant materials have emerged as most effective and are currently in various stages of development or industrial use. The four pottants are based on 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 170°C. Above 120°C during the lamination process, EVA and EMA undergo peroxide crosslinking to tough, rubbery thermosets. PnBA and PU are liquid casting systems. PnBA, a polymer/monomer syrup, is being developed jointly by JPL and Springborn Laboratories. PnBA is being formulated to cure within 15 minutes at 60°C. Candidate polyurethane systems are being supplied for FSA evaluation by various polyurethane manufacturers, and one promising PU system, designated Z-2591, has been identified. It is marketed by Development Associates, Inc., North Kingston, Rhode Island.

B. 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 (PMMA).

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 Pont Co.), and PMMA films (Acrylar, 3M Co.). Specific films and their cost are given in Table 2. Table 4 is a summary of evolving specifications and requirements for UV screening plastic film front covers.

Table 4. Evolving Specifications and Requirements for UV-Screening Plastic Film Front Covers

Description	Requirements and Specifications
Glass transition temperature (Tg)	>90°C
Non-hazing or cloudy	None at 80°C, 100% RH
UV screening	Total absorption at <0.36 μm
Thickness	≥1 mil
Total hemispherical light transmission (integrated over the wavelength ranges from 0.4 μm to 1.1 μm)	92%
UV Screening Agent	
Chemical consumption	None
Physical loss	None in water at 80°C
Weather-resistant bonding to pottants	No delamination allowed
Mechanical durability and weatherability on modules	Yes
Wrinkling	None
Crazing or cracking	None
Resistant to fracture and fatigue failure	Yes
Resistant to solvent stress cracking	Yes
Compatible with module fabrication	By lamination, casting, or both

An initial difficulty with Tedlar had been poor adhesion to EVA and EMA both for the clear UV-screening films functioning as front covers, and for white-pigmented Tedlar functioning as back covers on glass superstrate designs. Du Pont has identified an all-acrylic contact adhesive that can be coated directly onto one surface of Tedlar films. The coated adhesive, a Du Pont product designated 68040, is dry and non-tacky at ambient conditions; thus, coated Tedlar can be readily unwound from supply rolls. Du Pont experimental testing indicates that when the adhesive is heated during the EVA or EMA lamination cycle, strong adhesive bonding develops between EVA or EMA and the Tedlar films. The thickness of the adhesive coating investigated by Du Pont ranged between 0.3 mil and 0.4 mil.

An initial concern with Acrylar is its tendency to thermal shrinkage when heated above 105°C, the glass transition temperature of PMMA. This concern is greater with a free-standing film, but when uniformly pressed and constrained in a module assembly by lamination pressure, the film may be prevented from shrinking. Experimental evidence suggests that at 1 atm of lamination pressure, shrinkage is not a problem. However, reducing the lamination pressure to less than 1 atm could possibly allow some film shrinkage to occur. This has not yet been studied.

C. POROUS SPACERS

Fabrication of large-area modules by vacuum-bag lamination will require the use of air-release spacer materials at various interfaces in the prelaminated module-assembly stack-up. This requirement becomes more important for lamination pottants that tend to block or stick on contact with other surfaces. If air is interfacially trapped during lay-ups because of film blocking, it will be virtually impossible to exhaust this air from the module interfaces. Air exhaustion, even with non-blocking pottants, tends to become more difficult as the module area increases.

The air-release porous spacer material can serve additional useful functions. Substrate modules using metallic substrates, or glass-superstrate modules using metallic foils as back covers, must be fabricated in such a way that the electrical-insulation thickness between the solar-cell circuitry and metallic surfaces is maintained during fabrication. This can be accomplished by positioning an incompressible and nonconductive spacer between the solar cells and the metallic surface, which then prevents physical contact between the cells or interconnects and any metallic surface. The dielectric strength of the pottant, and the voltage difference to be insulated against, will result in a specification of absolute minimum thickness of pottant to ensure electrical isolation, avoidance of electrical breakdown, and subsequent arcing through the pottant. By selecting the thickness of the porous spacer used between the cells and metallic surfaces to be equal to or thicker than the absolute minimum requirement, reliable fabrication of a module with the required pottant insulation thickness is ensured as the spacer material becomes completely embedded in the pottant.

In summary, the interfacial spacer must be at least:

(1) Electrically nonconductive.

(2) Mechanically noncompressible.

(3) Porous for in-plane air flow.

(4) Inexpensive.

The best materials found to date satisfying these four criteria are non-woven glass mats manufactured by the Crane Co., Dalton, Massachusetts. The materials are sold under the trade name Craneglas, and are distributed by Electrolock, Inc., Chagrin Falls, Ohio. The specific mat being used in experimental modules fabricated with EVA is Craneglas Type 230, 5 mils thick, costing $0.0078/ft^2$.

The level of voltage achieved before electrical breakdown of EVA-encapsulated modules with this 5-mil spacer material has been investigated experimentally. Test modules were constructed with the following materials (top to bottom):

(1) Soda-lime window glass.

(2) 20-mil clear EVA film.

(3) Cell string.

(4) 5-mil non-woven glass mat.

(5) 14-mil white-pigmented EVA.

(6) 1-mil aluminum foil.

Under lamination pressure, the thickness of the non-woven glass mat would limit the minimum thickness of pottant between cells and the aluminum foil to the required 5 mils. However, cross-sectional measurements made on those modules indicate a pottant thickness of about 10 mils. The electrical breakdown voltage of several test modules was measured at 5.8 kV, ±0.2 kV.

Optical-transmission measurements have adequately demonstrated that the Craneglas spacer material can be used above the active surface of the solar cells (on the sun side) without loss of electrical performance or optical transmission. In fact, some preliminary evidence suggests performance enhancement, which is thought to be caused by internal light scattering and reflections involving the spacer.

D. SUBSTRATES

Structural panel materials that have been surveyed for potential application as module substrates include glass, metals, plastics, inorganics, paper products, and wood products. Included under inorganic products were bricks, tiles, ceramic slabs, resin-bonded sand, and glass-fiber-reinforced concrete.

If a 1986 module is at least 4 ft square, and if it is mounted in an open-lattice frame by perimeter attachment, then the substrate must support the mechanical loads over the module area that are generated by wind, hail, snow, etc. Accordingly, the lowest-cost structurally adequate material candidates become:

(1) Mild steel.

(2) Wood (hardboard panels).

(3) Glass-fiber-reinforced concrete.

1. Mild Steel

This is the least expensive commercially available metallic panel material, based on structural capacity for module application. An advantage of mild steel is that it can be fabricated as a flat panel with integral stiffening ribs on the back side. The stiffening ribs would reduce panel weight and thickness, compared with a panel without ribs carrying the same load. Optimization of a ribbed-substrate design is being studied.

Mild steel is available in hot-rolled and cold-rolled form. The cold-rolled form is the current candidate material undergoing FSA evaluation, at a nominal cost of about $0.0075/ft^2-mil. A disadvantage of mild steel is its corrosion sensitivity. Extensive work is under way to identify or develop the lowest-cost anti-corrosion coatings or surface treatments for mild steel. Coatings are preferred however, in order to more conveniently satisfy another requirement. The front and back surface of the mild steel should be white (actually a general requirement for substrates), and considering cost, this appears to be best achieved by use of white-pigmented anti-corrosion paints, or adhesively attached white-pigmented plastic films. Some commercial corrosion-prevention coatings under evaluation for mild steel are listed in Table 5, and white-pigmented plastic films are listed in Table 1.

Alternatives to mild steel are galvanized (zinc-coated) and enameled steel. In general, galvanized steel will cost about 20% more than mild steel. Steel sheet that can be enameled costs about 15% more than mild steel, and there are additional costs for the enamel and the enameling process. Since white front and back surfaces are needed, whether it be mild steel, galvanized steel, or enameled steel, mild steel with white corrosion protection coatings still appears to be the most cost-effective metal panel concept.

2. Wood

Wood is the least expensive structural material identified that could be used as a substrate panel for a perimeter-clamped, 4-ft-square module. Structural wood products are divided into two classifications: prime lumber and reconstituted wood products. The reconstituted wood products for large-area wooden panels, such as particle boards, plywood, fiberboards, etc., are useful as module substrates.

Of all of the varieties of reconstituted wooden panels, only two kinds are considered to be practical candidates: strandboards and hardboards. The latter are fiberboards with densities greater than 50 lb/ft^3. Both of these

Table 5. Commercial Corrosion-Prevention Coatings for Mild Steel

Coatings	Cost, Both Sides ($ft^2)
Polyvinylidene fluoride (primer + enamel) PPG Industries; 10-year outdoors	0.112
Silicone-polyester Dexter-Midland; prototype to 20-year	0.054
Polyester Dexter-Midland; 5- to 10-year outdoors	0.040
Acrylic coating PPG Industries; 5-year outdoors	0.040
Polyester (compliance coat) Dexter-Midland; 5-year outdoors	0.040
Acrylic emulsion coating Dexter-Midland	0.052
Polyester powder coating Dexter-Midland	0.056
Bonderite primer-treater conversion (to be applied before coating)	0.002

wood products are moldable and can be shaped as flat panels with integral stiffening ribs. With rib stiffening, the thickness of the hardboard need be only 1/8 in. Optimization of a panel rib design is being studied.

Hardboard panels are commercially available: Masonite Corp. markets several 1/8-in.-thick panels with modulus values in the order of 800 klb/in.^{2} to 10^6 lb/in.^{2}. The price of these panels is about \$0.12/ft^2. The specific hardboard being evaluated experimentally as a module substrate panel is Super-Dorlux.

U.S. Gypsum also markets a comparable hardboard panel, designated Duron, which is available in a 1/8-in. thickness, costing \$0.12 to \$0.13/ft^3, essentially the same as the Masonite hardboards.

Strandboard panels are being developed by Potlatch Corp. that will begin commercial production soon. Strandboard panels with modules values about 800 klb/in.^{2} are being manufactured for evaluation at pilot-plant production levels. The projected price of strandboard panels is about \$0.13/ft^2 to \$0.14/ft^2 for 1/4-in. thickness, and about \$0.16/ft^2 for 3/8-in. thickness.

However, the 3/8-in. thickness will probably be the thinnest such product to be marketed by Potlatch.

Thermal analysis indicates that the outdoor operating temperature of modules with a glass superstrate, mild-steel substrate, and 1/8-in.-thick wooden-panel substrate will be within 1°C of each other. The use of wooden panels thicker than 1/8-in. would increase the module operating temperature because of restricted bulk-thermal conduction to the back surface. Therefore, for array applications where module cooling can occur from front and back surfaces, the thinner, 1/8-in.-thick ribbed hardboards may be preferable. But for rooftop applications where module cooling may be restricted to occur principally from the front, and negligibly from the back, thicker wooden panels such as strandboards may be preferable, with the panel also becoming part of the rooftop structure.

The problem with wooden panels is hygroscopic expansion and contraction. For example, available data indicates that the thermal-expansion coefficient of hardboard is about 7×10^{-6} in./in. • °C, and that its hygroscopic-expansion coefficient is about 5×10^{-5} in./in. • % RH. Thus a 1%-RH fluctuation causes about the same expansion and contraction as a temperature change of 7°C.

Secondly, when hardboards with these kinds of thermal and hygroscopic expansion and contraction properties are processed during module fabrication in a vacuum-bag lamination up to 170°C, the hardboard will experience a net contraction from water dryout, and later, when returned to a humid environment, the wood will expand. Assuming that the encapsulated solar cells are at zero or near-zero mechanical stress at the end of the lamination cycle, gradual regaining of atmospheric moisture by the wooden panel to equilibrium with outdoor relative humidities imposes significant tensile strains (stress) on the solar cells, leading to cell cracking or interconnect failure.

Therefore, hardboards must be coated before lamination, in order to satisfy at least three requirements:

(1) The coating must limit wood dryout during vacuum lamination.

(2) The coating must limit the hygroscopic response of the hardboard to outdoor relative humidity fluctuations during service.

(3) The coating must be white.

Extensive investigations for white wood coatings meeting these requirements are under way.

3. Glass-Reinforced Concrete

Glass-reinforced concrete (GRC) substrate panels have been developed by Tracor MBA, San Ramon, California. The 4 x 8-ft panels are 1/4-in. thick, and have integral reinforcing ribs on their back sides. The projected cost of a panel is $0.62/ft^2, but this cost is partially offset by the fact that its inherent mechanical rigidity reduces the cost of rack materials required for outdoor mounting. Total-cost analysis indicates that

GRC may be cost-effective if it is part of the solar-array field-mounting structure and also serves as a module substrate.

Tracor MBA has manufactured a 4 x 8-ft demonstration module with this substrate material, using EVA as the encapsulation pottant, and clear, UV-screening acrylic films as the front cover. The demonstration module is mounted directly on 6 x 6-in. pressure-treated wooden posts, simulating an array field structure.

E. GLASS SUPERSTRATES

Structural and optical analysis of candidate glass materials has identified the most cost-effective glass superstrate as a low-iron, tempered soda-lime glass. An example of such a glass is Sunadex, available from ASG Industries, Inc., costing about \$5.50 to \$8.50/m^2, when purchased at the required high-volume level to obtain the lowest selling price.

F. BACK COVERS

Back covers are evolving from the specific protection needs of the back sides of low-cost modules. There are three back-side materials considered attractive for low-cost modules: wood and mild steel for the s[illegible]rate designs, and the pottant for glass-superstrate designs. Wood a[illegible]d steel require back covers for reasons stated earlier: moisture barri[illegible] wood, and corrosion protection for mild steel. Candidate white-pigmen[illegible]tic films for wood and mild steel back covers are listed in Table 1. For mild steel, candidate white-pigmented, anti-corrosion organic paints and coatings are listed in Table 5.

Glass-superstrate designs having polymeric pottant materials as back surfaces may need added protection from humidity or from back- scattered UV, or may need durable back covers for protection during storage, shipment, and mechanical action such as blowing sand. The need for a hermetic metal-foil back cover in the glass-superstrate design may be determined by the moisture sensitivity of different low-cost solar cell-metallization materials. The white-pigmented plastic films listed in Table 1 can also function as back covers for the glass superstrate design. In addition to these, metal foils or metal foils/plastic film lamination can also be considered for back covers. An extensive list of metal foil/plastic film laminate materials is given in Reference 1.

G. EDGE SEALS AND GASKETS

In addition to covering the back surface of a module for protection, the edge of an encapsulated module must also be sealed to prevent intrusion of water and other harmful environmental substances, and must be gasketed with a material that will cushion and isolate the edge against damaging stresses set up by perimeter clamping of a module in an outdoor mounting frame. The terminology, edge seal and gasket, connotes the dual requirement of atmospheric isolation and mechanical-stress cushioning, respectively, but does not necessarily imply that two or more discrete materials are required.

Table 6 documents a first effort at defining requirements for edge seals and gaskets for module application, which became guidelines for material surveys that still continue.

A critical property that is needed for elastomeric gasket materials is compression-set-recovery (CSR), which is a measure of the recovery of the material to its initial thickness after a compressive load is relieved. A corollary is that elastomers with good CSR should resist flow-out, creep, or decay from the internal stress of the elastomer. This internal stress, acting to restore the gasket to its initial thickness, is what maintains a tight fit.

Preliminary trends from cost and technical surveys for edge-seal and gasket materials suggest that butyls should be considered for the edge-seal material, and ethylene-propylene (EPDM) elastomers should be considered for the gasket material. A specific butyl edge seal and EPDM gasket materials that have been identified are given in Table 2. A cost analysis suggests that the combined cost of a butyl/EPDM edge seal and gasket, in high-volume usage to achieve the lowest possible price, should run between 10¢ and 18¢ per linear foot of module edge.

Table 6. Evolving Specifications and Requirements for Edge Seals and Gaskets

Item	Description	Requirements and Specifications
Edge Seal	Weather-stable, permanent adhesive material in common contact with gasket and module edges	Non-staining Tg <-40°C Liquid-water barrier Low water-vapor transmission Chemically inert Non-debonding Accommodates module expansion, contraction Resistance to mechanical fracture Restricted flow, creep, spread Low cost
Gasket	Elastomeric, one-piece, seamless stripping with channel filled with edge-seal material	Tg <-40°C Weather-stable Unplasticized Extrudable Accommodates module expansion, contraction Low compression set at 90°C Low cost Chemically inert

H. DIELECTRIC FILMS

The encapsulation materials enclosing the solar cells and their associated electrical conductors and terminals must also function as electrical insulation materials, isolating encapsulated high-voltage points from accidental human contact, and must have sufficient electrical resistance to prevent electrical breakdown or arc-through to external metallic parts in physical contact with the module. Included in this requirement is sufficient electrical insulation between metallic substrates or metallic foils that may be used in back covers, and the encapsulated solar cells with their electrical circuitry. The present FSA requirement is that the encapsulation system be capable of insulating against 3000 Vdc.

The electrical insulation of solar cells and their electrical circuitry must be provided by the non-metallic construction materials, such as glass, wood, elastomeric pottants, plastic-film front covers, etc. In these dielectric materials, either of two physical conditions for electrical insulation can exist:

(1) Flawless: The materials are flaw-free and their insulation resistance will be controlled primarily by thickness, which can be calculated from knowledge of the bulk materials's dielectric strength, which is typically expressed in units such as volts/mil.

(2) Flawed: e.g., bubbles, cracks, or embedded conductive contaminants in the dielectric materials; sharp points in the cell or electrical circuitry generating very high electrical-field intensities; delaminated interfaces that could result in current-leakage paths (accumulation of water). Some flaws can be inherent in the dielectric materials, but most are recognized as a consequence of poor design, poor workmanship, or inadequate quality control.

An experimental program to measure accurately the statistical distribution of dielectric strength of specific plastic films such as Mylar and Tedlar has been conducted by FSA. In films of constant thickness, large variations were encountered in measured breakdown-voltage values with measurements made at various surface locations on the films. The variations were apparently caused by flaws in the films, such as pinholes and thin spots, which were randomly distributed throughout the film samples. These data suggest that if breakdown voltage of dielectric materials is generally probabilistic, and in turn is related to a random flaw distribution throughout the materials' bulk volume, then in a module design a series of two or more dielectric-material layers should be used for electrical insulation to reduce greatly the probability of chance flaw alignment.

This concept, plus the characteristic of dielectrics that dielectric strength increases with decreasing thickness, suggests that the most cost-effective method of providing electrical insulation is a laminate of two thin dielectrics, rather than to thicken one dielectric material.

Since an encapsulated module has become a stack of discrete material layers satisfying various system requirements (see Figure 2), the concept of multiple layering of insulation materials to reduce the chance of flaw-related electrical breakdown is being designed into the modules. Therefore, at this stage of knowledge involving electrical isolation, the emerging information suggests the following two design guidelines for electrical isolation:

(1) Use of a minimum of two dielectric material layers above the solar cells, and two dielectric material layers on the back side of the solar cells.

(2) The minimum thickness of each dielectric layer should be capable of accommodating 3000 Vdc without electrical breakdown, based on the best knowledge of the intrinsic dielectric strength of the material.

Dielectric films are therefore additional film layers introduced into the module wherever needed in order to satisfy the "two-dielectric-requirement."

A description of the mild-steel substrate design follows: In this design, there are two dielectric layers above the solar cells, the pottant and a plastic-film top cover. On the back side of the solar cells, however, a single dielectric layer of pottant between the cells and the steel substrate would not satisfy the minimum two-layer requirement. As corrosion-prevention coatings are required on mild steel anyway, the requirement becomes that the thickness of this organic coating or plastic film be related to its dielectric strength for 3000-Vdc electrical-breakdown resistance. Thus a white-pigmented organic coating or plastic film on the sun-side surface of the mild-steel substrates has three functions:

(1) The second dielectric layer for electrical isolation.

(2) White background for internal light reflection.

(3) Corrosion protection of the mild steel.

I. PRIMERS AND ADHESIVES

During outdoor service, modules must resist delamination or separation of any of the encapsulant materials. Delamination of encapsullant materials can create voids for accumulation of water and therefore the potential of corrosive failure. Delamination of silicone elastomers from substrate surfaces was a common occurrence with Block I modules, but the incidences of silicone delamination with Block II and Block III modules decreased when adhesion promoters (recommended by the silicone manufacturers) were used.

It would be desirable to have all of the interfaces in encapsulation materials and between encapsulation materials and solar cells held together by environmentally stable primary chemical bonds. Some materials bond to each other chemically during the module fabrication process, but the majority of interfaces need weather-stable chemical-coupling primers or adhesives.

The inventory of primers and adhesives identified or developed to date for encapsulation materials undergoing FSA evaluation is given in Table 7. This table shows that many potential material interfaces remain for which

Table 7. Current Inventory of Adhesives and Primers for Encapsulation Materials Undergoing FSA Evaluation

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1. Primer for Bonding EVA and EMA to Glass

Component	Composition
Z-6030 silane (Dow Corning)	9.0 parts by weight
Benzyl dimethyl amine	1.0 parts by weight
Lupersol 101 (Pennwalt)	0.1 parts by weight
Methanol	90.0 parts by weight

2. Primer for Bonding EVA and EMA to Polyester Films

Component	Composition
Z-6040 silane (Dow Corning)	5 parts by weight
Resimene 740 (Monsanto)	95 parts by weight
Isopropanol	300 parts by weight

3. Adhesive for Bonding Tedlar to EVA and EMA

   68040 acrylic contact adhesive (Du Pont)

4. Primer for Bonding EVA to Aluminum, Mild Steel, Chrome Steel, Stainless Steel, Titanium, Brass and Copper

Component	Composition
Z-6030 silane (Dow Corning)	99 parts by weight
Zinc chromate powder	100 parts by weight
Benzyl dimethyl amine	1 parts by weight
Methanol	300 parts by weight

5. Primer for Bonding PnBA to Glass

Component	Composition
Z-6020 silane (Dow Corning)	10 parts by weight
Ethyl orthosilicate	10 parts by weight
Isopropanol	180 parts by weight
Water	2 parts by weight

6. Room-Temperature Adhesive for Bonding Scotchpar to Hardboard

   4910 Acrylic pressure-sensitive adhesive (3M)

Table 7. Current Inventory of Adhesives and Primers for Encapsulation Materials Undergoing FSA Evaluation (Cont'd)

7. Adhesive and Primer System for Bonding Scotchpar to Mild Steel (requires 20 minutes at $150^{\circ}C$)

Scotchpar	
Polyester film primer (No. 2 above)	3-component adhesive and primer system
EVA (A-9918 formulation)	
Metal primer (No. 4 above)	
Mild Steel	

8. Adhesive and Primer System for Bonding Tedlar to Mild Steel (requires 20 minutes at $150^{\circ}C$)

Tedlar	
68040 adhesive	3-component adhesive and primer system
EVA (A-9918 formulation)	
Metal primers (No. 4 above)	
Mild Steel	

primers and adhesives have yet to be identified. Some primers and adhesives currently under development are:

(1) Polyurethane to glass, and front-cover and back-cover plastic films.

(2) Acrylar to EVA and EMA.

(3) Tedlar to hardboard.

(4) Poly-n-butyl acrylate to front-cover and back-cover plastic films.

For those that have been identified, there still remains the demonstration of weather stability and module longevity.

Physically, the strength of an adhesive bond is measured under dry conditions, but for outdoor applications, the real assessment of an adhesive bond lies in the measurement of bond strength under wet conditions. When wet, the simple criteria of bond quality are that the bonded parts do not readily or easily separate and that there be some measureable bond strength, which is not a concern as long as the wet bond strength is sufficient to hold the parts together against the stress encountered in service.

In evaluating the durability of a chemically bonded interface, replicas of the bonded system are immersed in water at room temperature, and periodically the peel strength of a wet sample is measured. An excellent example of chemical bonding stability in water is seen in glass-fiber-reinforced boats, where the glass fiber is chemically coupled with silane to the laminating resin.

Experience indicates that under wet conditions, or exposure to moist atmospheres at high temperatures and humidities, the strength of the bonded interface generally decays logarithmically at a rate influenced by stress, temperature, and relative humidity. But the strength of the bonded interface recovers reversibly as environmental conditions become drier, and bond-strength decay begins again as moist conditions return. Fortunately, the bond strength does not seem to undergo cumulative damage with each cycle of exposure to moisture. This is important because outdoor weather patterns cycle from wet to moist to dry conditions and back again.

Emphasis has been placed on developing primer systems for EVA pottant, the first of the elastomeric pottants to reach an advanced stage of development. The primer system for EVA and glass (shown in Table 7) can be used optionally as either a wipe-on primer or as a compounding additive to generate a self-priming EVA.

This high-performance primer for EVA/glass has a long shelf life. Peel strengths of EVA on glass approach 40 lb/in. of width when dry, and only drop to near 32 lb/in. of width after 2 h exposure to boiling water. Preliminary testing indicates that this primer is equally effective for EMA/glass.

J. LOW-SOILING SURFACE COATINGS

Evolving soiling theories and physical examination of module surfaces suggest that surface 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.

These first two layers are resistant to removal by rain and wind. After the first two layers are formed, the third layer thereafter 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 suggest 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 based on 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, Conn., 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. Five months of test results to date are shown in Figure 5 for glass and Acrylar.

After 5 months outdoors, soil accumulation on the uncoated glass control has resulted in about a 3% loss of cell performance; the glass coated with L-1668 has realized only about a 0.5% loss. The uncoated Acrylar control has realized about a 5% loss, whereas the loss on the sample coated with perfluorodecanoic acid is only about 2.5%, and the loss on the Acrylar sample coated with L-1668 is about 3.5%. The test results are encouraging.

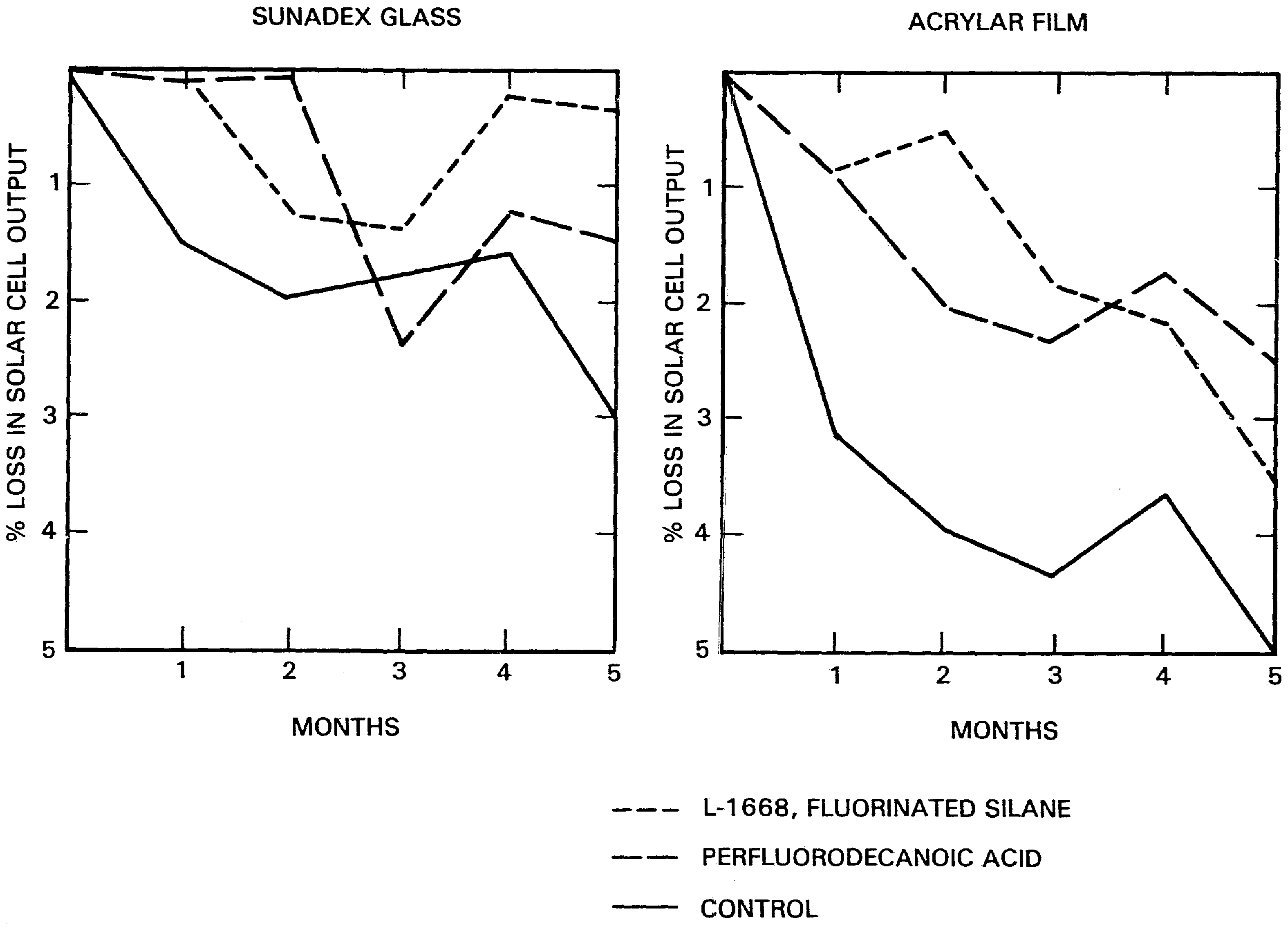

Figure 5. Experimental Evauluation of Low-Soiling Fluorocarbon Surface Coatings

SECTION III

ENCAPSULATION ENGINEERING

An engineering analysis of encapsulation systems is being 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) Minimum module temperature.

(4) Maximum optical transmission.

The engineering analysis is being carried out by a combination of computer modeling and experimental testing, to develop a general analytical method for analysis of all encapsulation systems and solar-cell devices.

The analysis to date has been carried out only for the encapsulation of 4-in. square, 15-mil thick single-crystal silicon solar cells in a 4-ft square module. The solar-cell spacing for this analysis was 0.05 in. (1.3 mm).

The key findings in the current analysis are summarized as follows:

A. STRUCTURAL ADEQUACY

Analysis has shown that:

(1) Tempered low-iron (Fe^{++}) soda-lime glass is recommended for a glass-superstrate design, for reasons of structural properties, optical properties, and cost in large-volume purchases. A 1/8-in.-thick tempered-glass plate meets the wind requirements for a 4-ft square module, but 3/16 in. may be considered if the trade-off is hail resistance.

(2) The magnitude of tensile stresses imposed on solar cells from module deflection or thermal expansion are regulated not only by the mechanical and thermal properties for the structural panel, but also by the Young's modulus and by the thickness of the pottant layer between the cells and the panel. Decreasing pottant modulus and increasing pottant thickness act to lower mechanical stress loads on the solar cells.

B. ELECTRICAL ISOLATION

Analysis has shown that:

(1) At least two dielectric encapsulation layers should be used above the cells and on the back side of the cells to minimize the probability of flaw-related electrical breakdown.

(2) Each of the four dielectric encapsulation layers should be sufficiently thick to each withstand 3000 Vdc, with the minimum thickness of each calculated on the basis of the best available dielectric strength value (V/mil) for the materials.

(3) The minimum thickness calculated for each dielectric layer is to be considered the design minimum in a module, but thickness may be increased if required for structural or other reasons. Electrical-isolation requirements establish minimum design thicknesses of the dielectric encapsulation layers for residential and utility applications.

C. MINIMIZING MODULE TEMPERATURE

Analysis has shown that:

(1) The relevant thermal properties of encapsulation materials regulating module operating temperature are thermal conductivity, infrared emissivity of the front and back surface, and solar absorption of the back surface.

(2) In terms of these thermal properties, module operating temperature is primarily regulated by the infrared emissivity of the front and back surfaces and secondarily by the thermal conductivity of the encapsulation material layers, except wood hardboards, if thicker than 1/8 in.

(3) Heat removal from modules is primarily regulated by the rates of heat dissipation from the surfaces by radiation and convection, and less by the rate of heat conduction from the cells to the surface through the various encapsulation layers.

(4) The dominant control on module operating temperature, which can be exercised through selection of encapsulation materials, involves the use of front and back-cover materials with maximum infrared emissivity (ϵ). Transparent glass and plastic-film front covers have ϵ values ranging between 0.85 to 0.90. Back-cover materials should also have very low solar absorptivity. The two requirements for the back cover are best satisfied using a white organic (non-metallic) material. Values of ϵ for white organic materials can be >0.90.

(5) Module design and field-engineering features that can help lower module operating temperature are the use of fins on the substrates (no horizontal cross fins), which also function as stiffening ribs. The mounting design should provide maximum accessibility of front and back surfaces to circulating air, and minimum exposure to scattered heat-producing radiant energy.

D. MAXIMUM OPTICAL TRANSMISSION

Analysis has shown that:

(1) Incident solar flux on either side (UV, IR) of the spectral-response range of silicon solar cells (0.4 μm to 1.1 μm), which is not reflected at the surface, is essentially absorbed by the module and converted to heat. This is because the transparent front materials are designed to be UV-absorbing, and they also have inherently strong infrared absorption bands. In addition to this, the silicon solar cell absorbs strongly in the infrared.

(2) Incident solar flux in the wavelength region of 0.4 μm to 1.1 μm should be transmitted maximally to the solar cells. The optical properties and features affecting this transmission are surface reflection (≈4%), AR coating on the solar cell, absorption bands in the encapsulation materials, and index-of-refraction mismatch at the interfaces.

(3) Front-side transparent encapsulation materials should have virtually flat transmission (no absorption bands) in the wavelengths from 0.4 μm to 1.1 μm, and an integrated transmittance ≥98%, after correcting for surface reflection losses of about 8%. Low-cost pottant candidates described in this document have these optical properties. Computer predictions of power output of modules with 10 to 25 mils of EVA indicated no effect of EVA thickness. High-iron (Fe^{+++}) glass has undesirable absorption in the wavelength region from 0.4 μm to 1.1 μm.

(4) AR coatings on silicon solar cells are a necessity. The AR coating should be optically matched with the pottant, but being optically matched with air is acceptable, resulting in only a small power loss when encapsulated. However, significant power loss occurs in cells without any AR coating.

(5) AR coatings on the module top cover surface are beneficial, if low cost and durability are enough to achieve a cost-benefit advantage. AR coatings on the second surface of glass, that is, at the pottant interface, tend to reduce transmission. Glass superstrates with AR coatings on both sides are not recommended.

(6) Computer analysis of normal-incident light on stippled glass, either stipple-up or stipple-down, found no optical effects, either beneficial or detrimental.

(7) Matching indexes of refraction of adjacent material layers are desirable, but if not done, back-reflection losses for the combinations of glass, plastic-film front covers, and pottant materials being considered are small because the index-of-refraction differences for these various materials are small. The best situation for mismatched index-of-refraction is to have them increase in each layer from the surface layer inward toward the cells. The reverse, decreasing index-of-refraction toward the cells, can result in power loss.

(8) Craneglas non-woven glass mats can be used above the solar cells without optical loss.

REFERENCES

1. Cuddihy, E., et al, Photovoltaic Module Encapsulation Design and Materials Selection: Volume I, JPL Document No. 5101-177, JPL Publication 81-102, DOE/JPL-1012-60, Jet Propulsion Laboratory, Pasadena, California, June 1, 1982.

2. Liang, R., et al, Photothermal Characterization of Encapsulant Materials for Photovoltaic Modules, JPL Document No. 5101-210, JPL Publication 82-42, DOE/JPL-1012-72, Jet Propulsion Laboratory, Pasadena, California, June 1, 1982.