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FINAL REPORT

on

EVALUATION OF AVAILABLE ENCAPSULATION MATERIALS FOR LOW-COST LONG-LIFE SILICON PHOTOVOLTAIC ARRAYS

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

for the

ENCAPSULATION TASK OF THE
LOW-COST SOLAR ARRAY PROJECT

The JPL Low-Cost Silicon Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

June 30, 1978

D. C. Carmichael, G. B. Gaines, G. T. Noel, F. A. Sliemers,
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ABSTRACT

This investigation was conducted as part of the Low-Cost Solar Array (LSA) Project that is managed by the Jet Propulsion Laboratory for the Department of Energy, Division of Solar Technology. The 1986 objectives of the LSA Project are to develop the technology and manufacturing capability to produce 500,000 kW/year of photovoltaic arrays at a cost of less than $500/kW, with an efficiency of greater than 10 percent and a service life of 20 years. One of the tasks (Encapsulation Task) of this project is concerned with the development and evaluation of the protective encapsulation-material systems which will be required to meet these cost and service life objectives, as well as the production and performance objectives for terrestrial photovoltaic arrays.

To help evaluate the requirements and potential of encapsulation systems for arrays, an extensive review and analysis was made, in a previous study, of prior world experience with photovoltaic arrays in the field and the service behavior of encapsulation materials for photovoltaic and related applications. In addition to an appraisal of field experience and problems, candidate materials for various functions in the array encapsulation system were recommended for investigation and pertinent properties of these materials were collected and reported in that study. The study that is reported here consists of the experimental evaluation of selected encapsulation designs and materials based on the earlier study which have potential for use in low-cost, long-life photovoltaic arrays.

The performance of candidate materials and encapsulated cells has been evaluated in this investigation principally for three types of encapsulation designs based on their potentially low materials and processing costs:

(1) Polymeric Coatings — Transparent conformal coatings over the cells with a structural-support substrate

(2) Polymeric Film Lamination — Cells laminated between two films or sheets of polymeric materials

(3) Glass-Covered Systems — Cells adhesively bonded to a glass cover (superstrate) with a polymeric pottant and a glass or other substrate material.

Several other design types, including those utilizing polymer sheet and pottant materials, were also included in the investigation.

Materials that are presently available were investigated for possible use in these encapsulation systems. Results are reported for 10 polymeric conformal coating materials, 4 polymer pottant, and 11 polymeric film and sheet materials. As candidates for bonding polymers to polymers or cells in the fabrication of arrays, 16 adhesives were subjected to screening evaluations. Glass materials that were studied for use as covers, and as substrates in some cases, included borosilicate glass; so-called iron-free, or low-iron-content glass; and soda-lime-float glass. Four polymer adhesives/pottants for use in fabricating glass-covered arrays were evaluated.

The cells used in this study were purchased from a commercial supplier and have an SiO_x *antireflection (AR) coating and a silk-screened Ag metallization. This metallization was selected for this study because it was known to be very sensitive to moisture and it is a potentially low-cost metallization for use in meeting the LSA Project cost goals.*

Evaluations of these materials are reported which include light transmittance measurements, moisture barrier properties, bond strengths, and particularly, the performance of encapsulated cells. To characterize the performance of these designs and encapsulation materials, measurements were made of as-manufactured cells, as-cleaned cells, encapsulated cells, and encapsulated cells that were exposed to different levels of ultraviolet radiation, high humidity, and temperature cycling.

It must be emphasized that the evaluations were conducted on commercially available materials and that development of processes for application of the materials to photovoltaic encapsulation was not within the scope of the study. In particular, the results reported for specific commercial materials do not reflect their use in applications for which they were developed and are currently employed, nor in their application to array encapsulation with process and materials developments. A specific purpose of this study was to identify directions for such process and materials research in the future.

Conclusions and recommendations resulting from the investigation which are described in the report are concerned particularly with the following areas:

(1) *Thin conformal coatings of the polymeric (i.e., acrylic and silicone) materials investigated do not provide sufficient protection for cells with silk-screened Ag metallization. Development efforts on materials and processes should be conducted to evaluate fully this potentially inexpensive type of encapsulation.*

(2) *Acrylic and Teflon FEP preformed films promise good weatherability and acceptable optical transmittance. More attention should be directed at their cost-effective use and adhesives should be selected or developed which provide adequate bonding and mechanical compliance to mitigate differences in expansion coefficients. Multiple-layer films, like the acrylic/polyester film investigated but possibly using other materials combinations, warrant future development and evaluation to establish their cost and performance potential.*

(3) *Borosilicate, low-iron, and soda-lime-float glasses represent viable candidate encapsulants for most environments. More work is necessary to select or develop optimum adhesives, edge seals, and back covers. The possible cost reductions resulting from large production and/or evaluations of glass composition versus properties versus cost should be investigated.*

(4) *Substantial advantages can accrue, with regard to overall system costs and technical performance, from integrating the AR coating, metallization and encapsulation into the cell and array design. Silk-screened Ag metallization, for example, has potential for lowering the cost of cell manufacture, but is very susceptible to degradation from moisture and requires an encapsulation system that provides a high degree of protection from the environment.*

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INTRODUCTION

The study described in this report was conducted in support of the Low-Cost Solar Array (LSA) Project(1,2), which is sponsored by the Department of Energy, Division of Solar Technology, and is managed by the Jet Propulsion Laboratory (JPL). The 1986 objectives of the LSA Project are to develop the technology and manufacturing capability to produce 500,000 kW/year of photovoltaic arrays at a cost of less than $500/kW, with an efficiency of greater than 10 percent and a service life of 20 years. One of the tasks (Encapsulation Task) of this project is concerned with the development and evaluation of protective encapsulation-material systems for these terrestrial photovoltaic arrays. Within this task, five interrelated studies have been conducted by Battelle's Columbus Laboratories:

Study 1: Review of World Experience and Properties of Materials for Encapsulation of Terrestrial Solar-Cell Arrays. Available data defining the state of the art of encapsulation-system materials and processes were collected and analyzed to provide a credible basis for defining initial materials evaluation and development efforts for the Encapsulation Task.

Study 2: Definition of Terrestrial Service Environments for Encapsulation Materials. Environmental conditions to which a terrestrial solar array will be exposed over a 20-year lifetime were characterized to aid definition of realistic test programs for encapsulation-system materials.

Study 3: Evaluation of Available Encapsulation Materials and Methods for Low-Cost Long-Life Silicon Photovoltaic Arrays. This study is the subject of this report.

Study 4: Development of Methodology for Designing Accelerated Aging Tests. Methods for life prediction of photovoltaic arrays were developed.

Study 5: Measurement Techniques and Instruments Suitable for Life-Prediction Testing of Photovoltaic Arrays. Diagnostic techniques for measuring changes in those materials properties that lead to degradation/failure were identified and analyzed and selected methods are being experimentally evaluated.

As indicated, this report presents the final results on Study 3. Separate final reports have been issued on Studies 1, 2, and 4(3,4,5), and an interim summary report on Study 5 has also been issued(6).

OBJECTIVE AND SCOPE OF PROGRAM

As background for the scope and objective of this study, it should be noted that at the beginning of the investigation it was generally acknowledged that silicon photovoltaic cells needed protection from atmospheric environments if the sought-for service life of 20 years was to be met. Confirmation of this need is shown subsequently in this report. Protective requirements stem from possible interactions of the atmospheric elements with the cell metallization, the antireflection

(AR) coating, and the p-n junction itself, especially at the exposed edge of the cell. Possibly there are AR coatings, metallizations, and passivation materials and techniques that would mitigate these interactions without total cell encapsulation. Materials and techniques that might serve these purposes are certainly not assured, however, and to the extent to which they are presently known, they would increase the cost to an unacceptable magnitude. Therefore, the most promising scheme for meeting cost and life goals is to totally encapsulate the cells, leaving some latitude in choosing AR coatings, metallizations, and passivation techniques on the basis of cost and important properties other than atmospheric stability.

Study 1 of the Battelle program reviewed the world experience with regard to encapsulation materials and techniques. The conclusions and recommendations of that study(3,7) led to the emphasis and scope of the present investigations. One major result was that materials used to date as array encapsulants were not suitable for achieving the life and/or cost goals of the LSA Project, making it mandatory to evaluate experimentally the potential of a wider range of currently known materials and techniques for encapsulation in order to determine their suitability and the directions for future research.

In addition, the earlier study identified the types of failures occurring in the field and, in some cases, under controlled exposures with the photovoltaic modules then extant. Some failures were identified which arose from lack of performance of individual materials: for example, excessive water permeation and lack of adequate light transmittance over time. More catastrophic-type failures occurred from the interactions at interfaces between different materials: delamination, for example. Both types of failures, again, dictated that further evaluations of materials be carried out. This investigation, for which the results are reported here, was directed toward the evaluation of selected, presently available materials that might meet life and cost goals after future development and/or increased production, with particular emphasis on avoiding these types of failures which have in the past limited the service life of photovoltaic modules.

It is to be emphasized that the evaluations were conducted on commercially available materials and that development of processes for application of the materials to photovoltaic encapsulation was not within the scope of the study. In particular, the results reported for specific materials do not reflect on their use for the applications for which they were developed and are currently employed, nor on their application to array encapsulation with process and materials developments. A particular purpose of this study was to identify directions for such process and materials research in the future.

This program was divided into two phases. Phase I involved an initial screening of potential encapsulants. To facilitate such a screening in a short period of time, replication of specimens was not stressed and many specimens were not replicated at all. Phase II was concerned with selecting the best candidate encapsulant subsystem from Phase I and with exposing five replicate specimens to the same environments. In this report, the results of Phase I and Phase II are presented separately.

Objective

The objective of this program was to evaluate selected materials and material combinations for use in encapsulation systems on the basis of (1) critical initial properties and characteristics and (2) their behavior over time in selected environments. The environments included high relative humidity, temperature cycling, and ultraviolet radiation. The emphasis was placed on screening evaluations, within the scope of the effort, to make possible initial comparisons for the many materials and material combinations in a relatively short time period, and to permit recommendations of materials and systems for subsequent development.

Initial evaluations in the study confirmed that the most meaningful evaluations were those made on actual encapsulated cells rather than on materials alone. Therefore, evaluations of the current-voltage (I-V) characteristics of encapsulated cells were emphasized in the study. Accordingly, encapsulated cells were fabricated using many material combinations and the electrical performance was measured after exposure to the various artificial environments. In the scope of this program, each cell was encapsulated individually; thus, the I-V characteristics reported represent one cell rather than cells in series or parallel combinations.

As noted, the types of failures identified in Study 1(3) suggested that the screening of materials and material combinations be performed on the basis of certain critical parameters. This program emphasized light transmittance, bond adherence between combinations of materials, moisture-barrier properties, and as pointed out above, the I-V characteristics of encapsulated cells.

Materials and Configurations Evaluated

Material and processing cost considerations suggest strongly that the design of the encapsulation system should be as simple as feasible. Prevention of types of failures previously observed with existing encapsulation systems suggests the same approach. Interfaces between dissimilar materials should be kept to a minimum. On the other hand, the requirements for the various elements of the encapsulation system differ considerably. The top cover must be transparent in the appropriate solar spectrum. It might or might not form a structural element of the design. Thus, there are forces to keep the number of materials in the design small, but, at the same time, there are forces that suggest the use of different materials for various elements so as to meet functionality requirements and furnish some choice in meeting material and processing cost constraints. In most designs envisioned to date, several different materials will be required, the choice depending on functionality. Accordingly, the selections of materials and material combinations to be evaluated in this study were made on the basis of required functions in selected encapsulation designs that appeared promising for meeting cost, production, and performance (i.e., efficiency and lifetime) goals.

Guidelines for Materials Selection

Property guidelines used in the selection of candidate encapsulant materials are identified in Table 1. In terms of specific properties, transparency in the appropriate range of the solar spectrum was a primary consideration in the selection of all materials exclusive of the substrates discussed below. Other properties/characteristics that were weighed particularly heavily were weatherability, useful temperature range, and processability. The latter includes handleability, repairability, and ease of automation. Materials costs and availability also were of particular importance in the selection process. However, because both processing considerations and the finalized system design(s) are basic to the establishment of total system costs, certain materials having relatively high unit costs (e.g., certain silicones, epoxies, and fluorocarbons) were selected for consideration. These materials appear to fulfill functions in certain conceptualized designs for the encapsulation system that cannot be obtained with lower cost materials. The use of such materials depends upon what design modifications might be made, if necessary, to *minimize the amounts of certain of these high-cost materials required* while maintaining their unique system functions. Ultimately, it is anticipated that materials development programs are likely to provide less-expensive replacements for, or modifications of, these materials. For this program, the emphasis was put on existing materials. It should be noted that the materials candidates that have been examined in this study are, in many cases, representative of a number of viable ones available from a variety of manufacturers/suppliers.

TABLE 1. PROPERTY GUIDELINES USED IN MATERIALS SELECTIONS

Cover

Low cost

Transmittance

UV stability/weatherability

Abrasion resistance

Barrier properties (e.g., to moisture)

Low adhesion of dirt and other pollutants

Appropriate structural properties(a)

Adhesive

Good adhesion to cover and substrate

Low cost (including primer, if necessary)

Transmittance (depending on location)

UV stability/weatherability

Low modulus (probably)

Forms moisture barrier with cell/cover

Substrate

Low cost

Moisture barrier

Weatherability

Appropriate structural properties(a)

(a) Structural properties required depend upon design of encapsulant system.

The identification and characterization of all materials of potential interest for each end-use application (adhesives, coatings, etc.), of course, is not feasible. It is believed, however, that the materials selected are consistent with the general property requirements of interest for terrestrial solar-cell encapsulation. A discussion of the selected materials according to the several end-use applications follows.

Selection of Materials Evaluated for Polymeric Encapsulation Systems

Adhesives. Adhesives can be classified either as structural or nonstructural. Generally, the former are load-bearing materials that will strengthen structures, often to the extent that the bond becomes as strong or stronger than the materials joined. These high-strength materials are resin based and are used to join various types of materials: metals, glass, plastics, etc. For the most part, they are thermosetting types and available both as dry film (prepreg) and as liquid resins. Generally, curing is effected with heat. Most epoxy adhesives are examples of this class of materials.

The nonstructural adhesives are non-load-bearing, and are used with a variety of materials where there is no need for high stress resistance. They are thermoplastic, or noncuring, and can have either a rubber or resin base. Certain silicones and urethanes are examples of the rubber-based adhesives; certain acrylics are representative of the resin-based nonstructural systems.

The high strength attributable to the structural adhesives generally is accompanied by a high degree of rigidity. The rubber-based nonstructurals, on the other hand, have excellent flexibility. Between these two extremes are the resin-based systems.

From the standpoint of the utilization of adhesives in solar-cell encapsulation, considering various potential designs for the ultimate encapsulant system(7), both the structural and nonstructural materials classes must be considered. However, in the current work, emphasis has been placed on the use of low-modulus materials and, consequently, nonstructurals predominate. The adhesives selected for evaluation are listed in Table 2. It is recognized here, as in the selection of materials examples for other types of end-use applications, that a number of other materials representing the same classes may provide equally good, or possibly superior, properties for the encapsulation task.

Adhesives candidates for bonding silicon cells to the plastic cover must be clear and UV stable. Of the structural types, the epoxy (Scotch-Weld 2216 B/A, clear) or an aliphatic-isocyanate-cured urethane have the best potential if flexibility and moderate strength are desirable. Also acceptable are such nonstructurals as Acryloid B-7 (acrylic), Silastic 732 RTV or RTV 118 (elastomeric silicones), and Silgrip SR-573 (silicone resin).

For certain bonding applications associated with cell encapsulation (e.g., substrate-to-cell bonding), optical clarity and UV stability are not necessary requirements. Scotch-Grip 4475 and 4693 are adhesives of this type. They have been studied primarily because of their excellent bond strengths to certain plastics. Adhesives of this type also are important from the standpoint of applicability to high-speed film laminations with good bond strengths.

TABLE 2. SELECTED ADHESIVES CANDIDATES

Trade Name	Manufacturer/Supplier	Class
	STRUCTURAL	
Cavalon 3100S (TS)[a]	Du Pont	Room temp. curing acrylic
Scotch-Weld 2216 B/A	3M	Room temp. curing epoxy
Scotch-Weld 3520 B/A	3M	Room temp. curing epoxy
Structural 3532 B/A	3M	Room temp. curing urethane
	NONSTRUCTURAL	
Acryloid B-7 (TP)[a]	Rohm & Haas	Thermoplastic acrylic
B-2397-10	Hughson	Laminating urethane
Chemlok 7000/7203	Hughson	Laminating urethane
Chemlok 7002/7203	Hughson	Laminating urethane
DC 282	Dow Corning	Pressure sensitive silicone
RTV 118	G.E.	Room temp. curing silicone
Scotch Grip 4475	3M	Resin contact (plastic)
Scotch Grip 4693	3M	Elastomeric contact
Silastic 732 RTV	Dow-Corning	Room temp. curing silicone
Silastic 734 RTV	Dow-Corning	Room temp. curing silicone
Silgrip SR-573	G.E.	Heat sealable silicone
Silgrip SR-574	G.E.	Pressure sensitive silicone

(a) The abbreviations TS and TP designate thermosetting and thermoplastic materials, respectively.

Cover Films and Sheets. In discussing the selection of materials for use as covers in encapsulation systems, the distinction between films and coatings (discussed later) is made on the basis that films are separate structural units formed prior to application. As such, they are generally distinguished from sheet materials only arbitrarily, on the basis of thickness. The dividing line is not well defined, but certainly materials less than 500 μm (≈20 mils) thick are considered to be films, while those with thicknesses of 1600 μm (≈1/16 inch) or more can be classified as sheet.

Film and sheet selections evaluated in this study are listed in Table 3 and have been drawn primarily from the acrylic, halocarbon, polycarbonate, and thermoplastic polyester materials classes. These classes have provided a broad range of moduli from very flexible to quite rigid. Also identified in Table 3 is a specialty film material, 3M Company's Flexigard. It is a film laminate proposed by the manufacturer for use as outer windows of solar collectors. Film/sheet materials can be used as protective materials (moisture barriers) for the underside of the encapsulant design as well as in cover applications. Aclar-type film, for instance, is especially good for moisture-barrier properties.

Figure 1 conceptually represents a design for encapsulation of cells by polymer-film lamination.

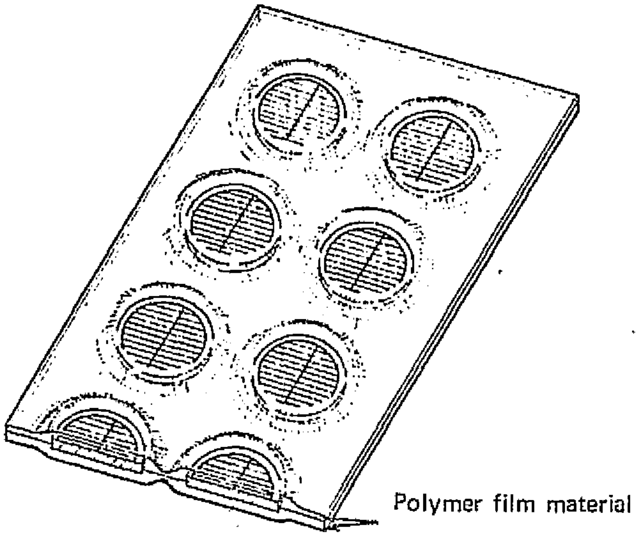

FIGURE 1. CONCEPTUAL REPRESENTATION OF ENCAPSULATION BY POLYMER-FILM LAMINATION

Polymer film is bonded adhesively or heat sealed.

Coatings and Pottants. In considering various designs for the encapsulation of solar cells, polymeric coatings may find utility in any of a number of different protective applications. They may be of value (1) in improving the resistance to ultraviolet (UV) radiation, abrasion, and other environmental effects on a protective cover, (2) in protecting soft potting compounds from dirt and other environmental hazards and in facilitating the removal of ice and snow from such materials, (3) in relieving thermal stresses between other components of the assembly, and (4) providing high electrical insulation between system components and a barrier against moisture and other environmental effects through direct application to the silicon cells and interconnects.

TABLE 3. SELECTED COVER CANDIDATES

Trade Name	Manufacturer/Supplier	Class	Thickness, µm (mils)
		Film	
Aclar 33C	Allied	Halocarbon	51 (2)
Dyed Mylar (weatherable)	Martin Processing Co.	Polyester (TP)[(a)]	178 (7)
Halar	Allied	Halocarbon	127 (5)
Korad A	Xcel	Acrylic	153 (6)
Flexigard	3M	Acrylic-Polyester	127 (5)
Tedlar 400 BG20TR	Du Pont	Halocarbon	102 (4)
"Teflon" FEP (Type C)[(b)]	Du Pont	Halocarbon	127 (5)
Tuffak No. 90230-D	Rohm and Haas	Polycarbonate	508 (20)
		Sheet	
Acrylite	American Cyanamid	Acrylic	3175 (125)
Lexan 9030 (UV - stab.)	G.E.	Polycarbonate	3175 (125)
Sun-Lite (Premium)	Kalwall	GR Polyester	635 (25)

(a) TP designates thermoplastic-type material.
(b) Type C is treated on one side to promote bonding.

The selected list of coatings and pottants for evaluation is shown in Table 4 and includes the acrylic, epoxy, urethane, poly(vinyl butyral), and silicone classes of materials. The list includes materials that may be of interest directly as solar-cell coatings as well as general-purpose coatings for various components of the encapsulation system.

Coatings with clarity, UV stability, moisture resistance, and moisture-barrier properties would be ideally suited for conformally top coating the solar cell. Figure 2 conceptually illustrates such an array. Most coatings in the table above were selected for such an evaluation.

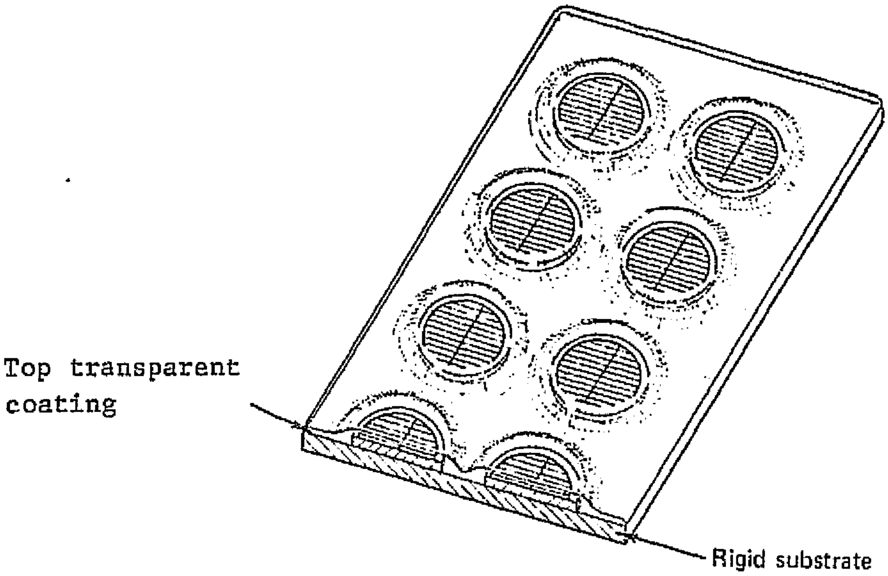

FIGURE 2. CONCEPTUAL REPRESENTATION OF ENCAPSULATION WITH A POLYMER CONFORMAL TOP COATING

Cells are adhesively bonded to a rigid substrate.

Pottants (or potting compounds), generally, are one- and two-component liquid systems. Potting is an embedding process in which the material or mixture of materials is "poured" into a "container" and bonds directly to it. Usually no mold is used, and the container becomes an integral part of the assembly.

The problem areas associated with the potting of electronic components include high curing exotherms, resin shrinkage and subsequent stress development, inadequate thermal-shock resistance of materials and components, process-control problems associated both with raw materials and processing, and outgassing and corrosivity problems. For the LSA Project, these problems are compounded by the added requirements for optical clarity and small coefficient-of-expansion differences with silicon, at least in the majority of envisioned encapsulation designs.

In Table 4, pottant Q3-6527 A and B requires heat to accelerate cure, although it will gel at room temperature in 24 hours. Heat also will speed the cure of Sylgard 184. Two design types that utilize pottants are illustrated in Figures 3 and 4.

TABLE 4. COATINGS AND POTTANT CANDIDATES

Trade Name	Manufacturer/Supplier	Class
	Coatings	
Butvar B-79	Monsanto	Poly(vinyl butyral)
Butvar B-98	Monsanto	Poly(vinyl butyral)
Butvar BR	Monsanto	Poly(vinyl butyral)
Butvar Dispersion FP	Monsanto	Poly(vinyl butyral)
DC-3140 (1204 primer)	Dow Corning	Silicone
Eccocoat AC-8	Emerson and Cuming	Acrylic
Eccocoat RTU	Emerson and Cuming	Urethane
Eccocoat VE	Emerson and Cuming	Epoxy
Glass Resin 650 (50%)	Owens-Illinois	"Silicone"
Glass Resin 650 (25%) (GR-70105-2)	Owens-Illinois	"Silicone"
	Pottants	
Q3-6527 A/B (gel)	Dow Corning	Silicone
RTV-615	General Electric	Silicone
RTV-655	General Electric	Silicone
Sylgard 184	Dow Corning	Silicone

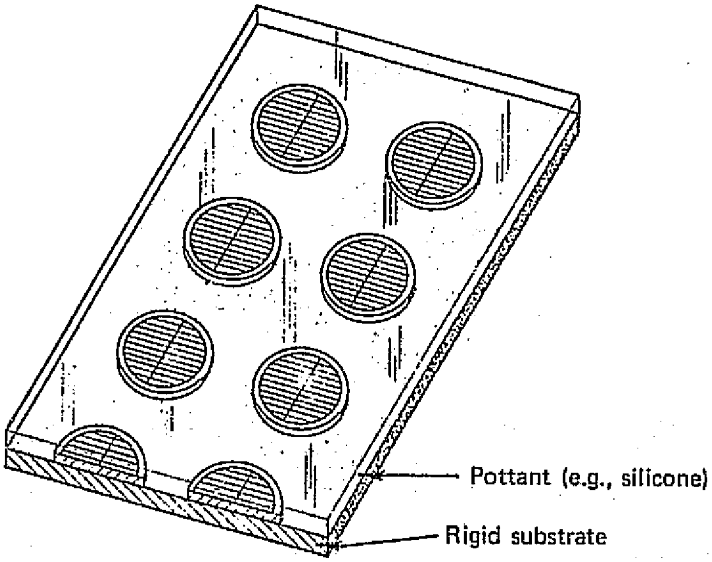

FIGURE 3. CONCEPTUAL REPRESENTATION OF ENCAPSULATION USING A POLYMER POTTANT

Substrate is rigid and can be picture-frame type into which pottant is poured.

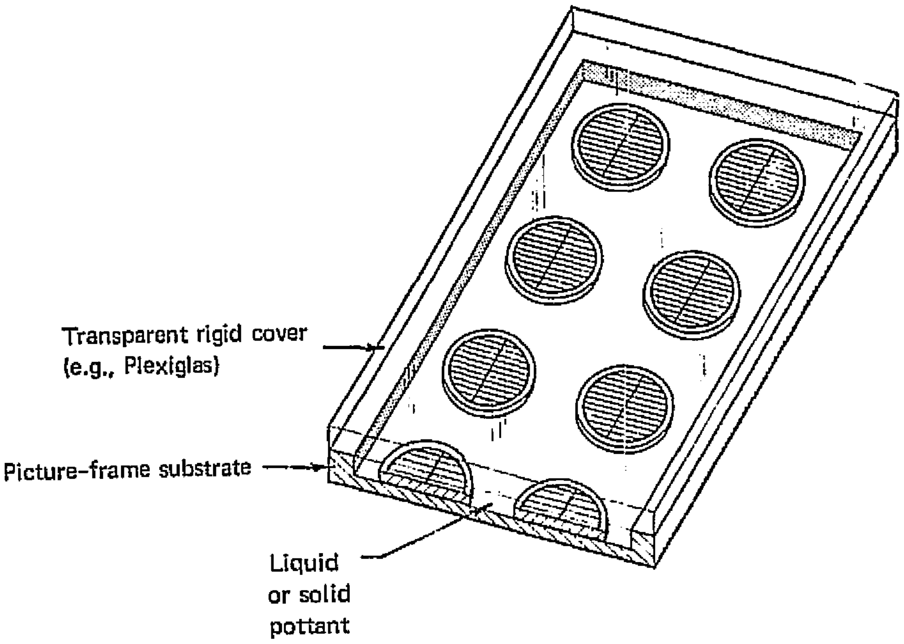

FIGURE 4. CONCEPTUAL REPRESENTATION OF BOX-TYPE ENCAPSULATION USING A POLYMER POTTANT

Cells are adhesively bonded to substrate. Liquid refractive-index matching pottant, gel, or solid pottant can be used.

The option of using a coating on the underside of the solar cell (illustrated in Figure 5) requires that the coating be selected on the basis of three principal properties. These are adhesion, weathering resistance, and low moisture permeability. In such an encapsulant design, it is likely that the top of the cell would be bonded to a clear cover (glass or polymer). Coatings for this application need not be clear, and could include materials based on butyl rubber (Butyl LM430-Exxon), polyisobutylene, polyvinylidine chloride-polyvinyl chloride copolymer, and halocarbons resins. Silane or titanate coupling agents can be used to achieve good bonding where marginal adhesion of the coating to the solar cell is experienced. (Alternatively, metal foil or sheet can be used if insulated from the cells and interconnects.)

Substrates. A number of materials types are candidate substrates, including metals, glasses, and polymerics. In considering the polymer materials, reinforced materials or laminated structures are viable forms for the thermal and mechanical requirements (e.g., epoxies and polyesters).

In considering reinforced sheet materials it was anticipated that the sheet would likely be bonded, either adhesively or mechanically, to a suitable retaining structure to form the final assembly. It has been recognized, of course, that certain system designs may not require a structural substrate as defined here. For example, the roofing-shingle or roll-out blanket-type designs would be attached directly to a retaining system without a substrate as defined.

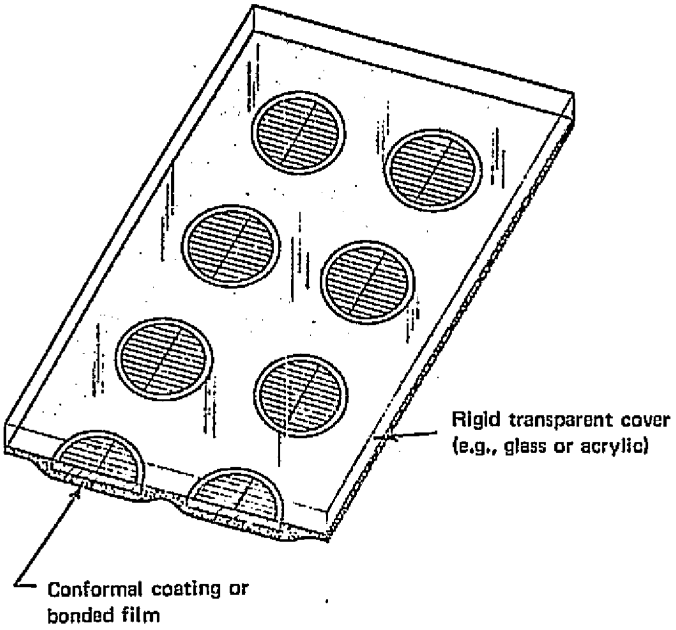

FIGURE 5. CONCEPTUAL REPRESENTATION OF ENCAPSULATION USING A RIGID TRANSPARENT COVER AND BACK POLYMER COATING OR FILM

Cells are adhesively bonded to cover.

Other Substrate Materials. Two other materials, a 102-μm (4-mil) aluminum foil and an 89-μm (3.5-mil) composite (Alure CX) were used as substrates in several film-laminate encapsulant constructions. The latter material (St. Regis) is composed of a 13-μm (0.5-mil) metallized polyester and a 76-μm (3.0-mil) coextruded high-density polyethylene. It is reported to have excellent water vapor barrier properties. Wood products coated steel sheet and styrene foams (see Addendum) are also candidates but were not included in the scope of this evaluation.

Selection of Materials Evaluated for Encapsulation Systems Employing Glass

Glasses have a long service history, and, in general, have shown good weatherability and light transmittance. Moreover, they can be employed as structural elements provided certain risks are accepted from hazards due to their brittleness. The structures evaluated in this program, employing a glass component, are identified in Figure 6 and described as follows:

Type A. A cell with attached (soldered) leads was sandwiched between two glass panels with adhesive between both of the cell surfaces and the glass panels. Thus, the cell was completely enclosed in adhesive.

Type B. This configuration is the same as Type A, except some of the outer diameter of the cell was not encased in adhesive (thus allowing direct cell exposure to the test atmosphere).

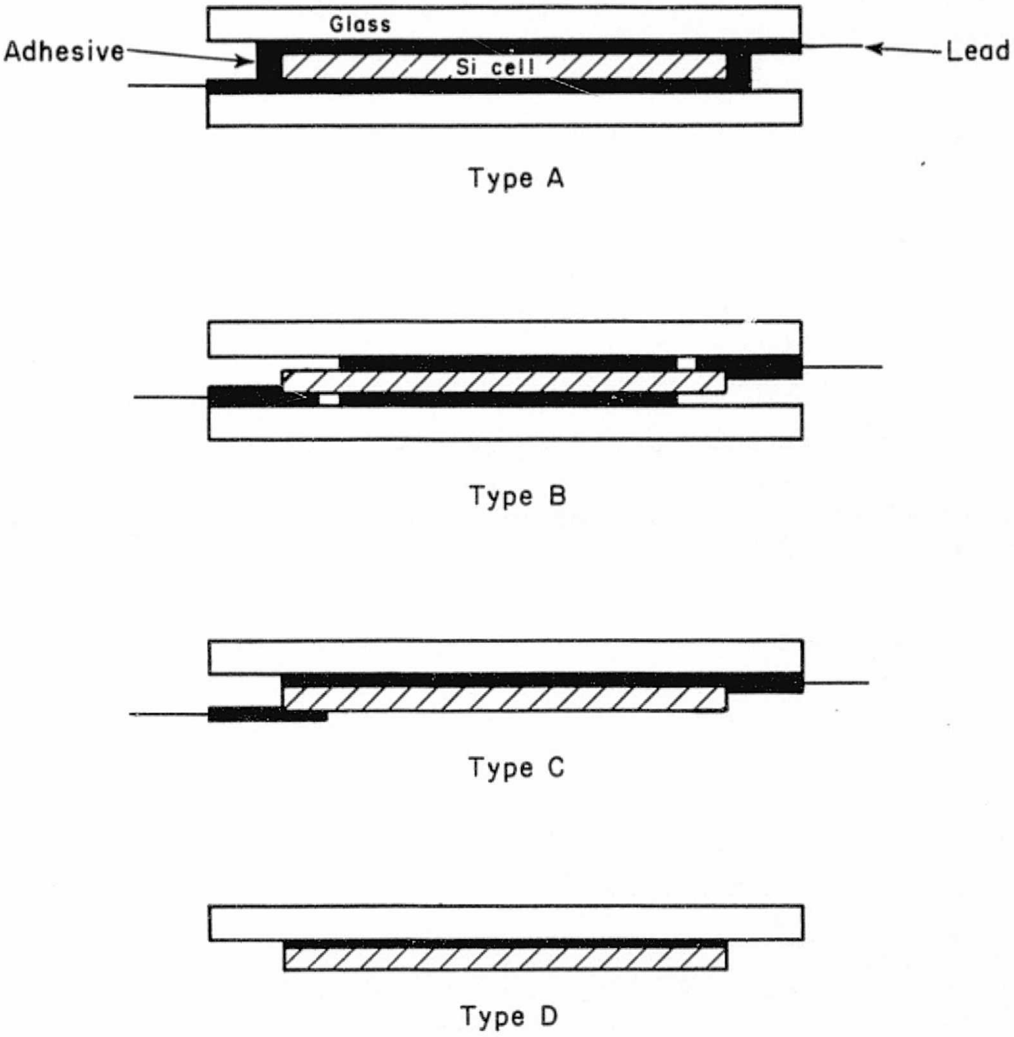

FIGURE 6. TYPES OF SOLAR CELL/ADHESIVE/GLASS LAMINATES EVALUATED IN ENVIRONMENTAL SCREENING TESTS

Type C. A cell with attached leads was adhesively bonded to a cover glass panel. The back side of the cell was not covered, thus allowing access to the test environment.

Type D. This was a configuration for examining the delamination susceptibility of thin [76 to 127 μm (3 to 5 mils)] adhesive layers. This type excluded the leads to permit thinner adhesive layer bonding to the cover glass.

None of the laminates examined in Phase I employed a "hermetic" edge seal. This was done to test the adhesive or cell (depending on the laminate type) if exposed to the environment. A lead-tape edge seal was employed in Phase II.

Adhesives. The adhesives evaluated are identified in Columns 1 and 2 of Table 5. On the basis of the combination of long life expectancy and thermal-stress accommodation, the silicones are prime candidates for bonding cells to glass covers. The three candidates selected represent a range in characteristics in processing and application as well as mechanical properties. The Sylgard 184 is a two-part potting resin which has prior history of use in solar-cell array fabrication. The Dow 3140 is a noncorrosive, moisture-cured rubber used as a conformal coating or for encapsulation of electronic components. The silicone Gel Q3-6527 has very low modulus and should accommodate large thermal-expansion mismatch between cells and cover glass.

Plasticized polyvinyl butyral (PVB) was included because of its long-established use in laminated glass for outdoor exposure, because it is presently being used in glass encapsulation of solar cells, and because thermal-stress calculations by JPL indicated its suitability in terms of thermal-stress accommodation.

Glass Cover Materials Selection. Two glass candidates were included in Phase I: a soda-lime float glass and 7740 borosilicate. The soda-lime glass represents a high-expansion, low-cost glass. The 7740 represents a low-expansion, high-transmission, and more expensive type of glass. In Phase II, an "iron-free" (low iron content) glass, which has higher transmission but is more expensive than soda-lime glass, was also studied.

TABLE 5. MATERIALS AND SPECIMEN TYPES (TEST LAMINATES) AND ASSOCIATED SCREENING TESTS CONDUCTED ON SPECIMENS WITH GLASS TOP COVERS

Some specimen types (see Figure 6) also had glass substrates.

Adhesive Material						Screening Tests[b]		Examination/Evaluation	
Type of Polymeric Material	Commercial Designation	Adhesive Thickness, µm(mils)	Primer Used	Glass Used	Test Laminate Description[a]	-40 to +90 C Cycles/Day	UV Exposure	Visual Microscopic Examination	Electrical[c] Characterization
Two-component silicone	Sylgard 184	≈508 (20)	Q36-060	Soda-Lime float	Type A	x	x	x	x
Ditto	Ditto	Ditto	Ditto	Ditto	Type B	x	x	x	x
"	"	"	"	"	Type C	x	x	x	x
"	"	76-127 (3-5)	"	"	Type D	x	x	x	
"	"	≈508 (20)	"	7740 borosilicate	Type A	x	x	x	x
"	"	Ditto	"	Ditto	Type C	x	x	x	x
"	"	76-127 (3-5)	"	"	Type D	x	x	x	
One-part noncorrosive silicone rubber	Dow 3140	≈508 (20)	1204	Soda-Lime float	Type A	x	x	x	x
	Ditto	Ditto	Ditto	Ditto	Type B	x	x	x	x
Ditto	"	"	"	"	Type C	x	x	x	x
"	"	76-127 (3-5)	"	"	Type D	x	x	x	
"	"	≈508 (20)	"	7740 borosilicate	Type A	x	x	x	x
"	"	Ditto	"	Ditto	Type B	x	x	x	x
"	"	"	"	"	Type C	x	x	x	x
"	"	76-127 (3-5)	"	"	Type D	x	x	x	
Silicone gel	Q3-6527	≈508 (20)	None	Soda-Lime float	Type A	x	x	x	x
Ditto	Ditto	Ditto	Ditto	Ditto	Type C	x	x	x	
"	"	76-127 (3-5)	"	"	Type D	x	x	x	
"	"	≈508 (20)	"	7740 borosilicate	Type A	x	x	x	x
"	"	76-127 (3-5)	"	Ditto	Type D	x	x	x	
PVB	Saflex[d] or Butacite	762 (30)	No	Soda-Lime float	Type A	x	x	x	x

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(a) See Figure 6 for sketches of laminate types. Types A, B, and C contain electrical leads to the cells; Type D does not.

(b) Laminates were sequentially exposed to 1 week of thermal cycling and 1 week in UV Weatherometer cabinet employing a Xenon lamp source.

(c) Electrical measurements made are discussed in a separate section of the report.

(d) Saflex is manufactured by Monsanto, Butacite by Du Pont. The performances of both products are expected to be similar.

EXPERIMENTAL TECHNIQUES AND PROCEDURES

The experimental techniques and procedures used in the study are described in this section. These were chosen consistent with the goal to discriminate among materials and material combinations in a short period. The emphasis was on screening techniques rather than the development of unique new tests.

Identification of Solar Cells Employed in the Encapsulant Evaluation

A substantial portion of the evaluation of encapsulant materials was augmented by measuring the current-voltage (I-V) characteristics of commercial solar cells which were encapsulated by the selected materials or material combinations. For all of the measurements reported, a single type of cell was utilized. The identifying features are listed below.

- Supplier: Spectrolab, Sylmar, California
- Material: Silicon (n/p)
- Dimensions: Round disc, 5.1 cm (2 in.) in diameter
  0.25 to 0.30 mm (10 to 12 mils) thick
- Metallization: Silver, silk screened
- Antireflecting coating: SiO_x.

According to the supplier, the metallization is applied by thick-film techniques. Different silver "pastes" are used for the collector grid and back (solid) contacts. Annealed copper leads were soldered to the metallization grids and back collector.

I-V characteristics were measured in the as-received (unencapsulated) condition for each cell for which encapsulated data are reported. It is to be noted that considerable nonuniformity in characteristics was measured among the cells used. Efficiencies ranged from approximately 8 percent to 13 percent. In most of the results reported, changes in cell parameters rather than absolute values are given so as to obviate these nonuniformities to some degree.

Measurement of the Cell Parameters

Specific cell parameters were measured in the as-received condition, after cleaning, after initial encapsulation, and after exposures to a particular environment for a measured length of time. The environments are described in subsequent paragraphs of this section of the report. The parameters determined were:

- Open-circuit voltage, V_{oc}
- Short-circuit current, I_{sc}
- Maximum power, P_{max}
- Current at maximum power, I_{max}

- Voltage at maximum power, V_{max}
- Fill-factor (electrical), F.F.
- Series resistance, R_s
- Shunt resistance, R_{sh}
- Efficiency, in percent, η.

These parameters assume the conventional equivalent circuit wherein a current generator is in parallel with an ideal diode and a shunt resistor. A resistance is in series with the load.

The light source for the cell measurements consisted of 4 ELH lamps (General Electric or Sylvania) mounted in a lighttight enclosure and radiating onto a water-cooled copper plate 50 cm from the lamps. A regulated supply powered the 300-W lamps. A light intensity of 100 mW/cm^2 was employed for the "high-intensity", or standard, measurement. This quantity was determined with a standard cell fabricated by NASA LeRC (Standard Cell Z-34). To facilitate the measurement of the series resistance, a "low-intensity" measurement was also taken at approximately 75 mW/cm^2. The I-V curve was traced out with a bucking voltage supply.

With one exception, all parameters were either read from the traced-out curve or calculated in the conventional manner. The one exception was the shunt resistance, R_{sh}. This value was obtained by simply measuring the resistance of the cell under no illumination while applying a back bias of approximately 1 volt. Figure 7 shows the form on which the cell characteristics were recorded, along with several cell parameters.

Cell Cleaning Procedures

A first consideration in the preparation of test laminates was adequate cleaning of the silicon solar cells which had silk-screen-applied silver metallization and SiO_x antireflective coatings. Cleaning materials/procedures were desired to remove organic contaminants which might interfere with adhesive bonding, but which would not degrade the electrical characteristics of the cells. Initial solvent procedures utilized methanol, toluene, and acetone. These were selected to provide solvents representative of three types of hydrogen bonding and resulting solvent characteristics. They were intended to remove the solder flux and any organic contaminants from the cell surface. A methanol soak was employed as the first step, followed by either a toluene or acetone soak and finally by the remaining third solvent in a vapor/liquid cleaning step.

On the basis of measurements of pre- and postcleaning electrical characteristics of the cells, the use of the three above solvents did not yield consistently favorable results. In some cases, the shunt resistance and the efficiency of the cell were significantly lowered. Efforts to utilize ultrasonics to enhance the thoroughness of cleaning were deleterious. Such a treatment tended to erode the metallization at areas of apparently weak bonding. An alternative and preferred cell cleaning procedure was settled upon for this study which was based upon water and Freon TE. Cells were first rinsed and then soaked for 5 minutes in a 95 weight percent ethanol-5 weight percent water solution. They were then rinsed with Freon TE and vapor degreased in the Freon TE. Finally, the cells were vacuum baked at 100 C for 30 minutes. Table 6 compares the electrical characteristics of several of the cells prepared using this cleaning procedure with their initial characteristics. As the table indicates, the cell characteristics before and after cleaning were essentially the same.

Run INITIAL Cell 060 Date 1/27/77

Cell Treatment AS RECEIVED

V_{oc} =	0.572 volt	I_{sc} =	581 ma	V_{mp} =	0.460 volt
I_{mp} =	518 ma	P_m =	238 mw	η =	13.2 %
F.F.=	0.717	R_s =	0.102 ohms	R_{sh} =	1340 ohms

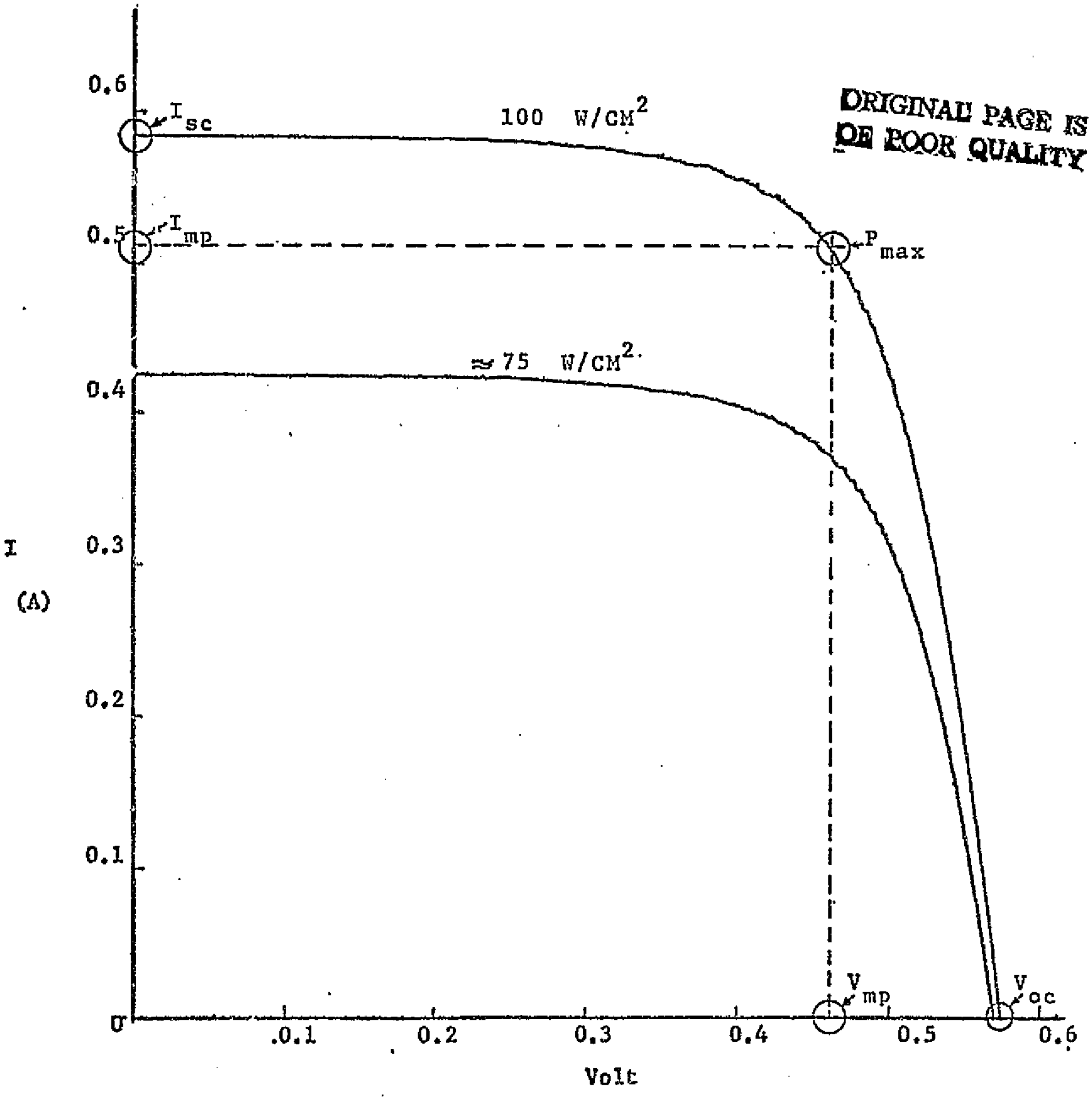

FIGURE 7. TYPICAL FORMAT AND I-V CHARACTERISTICS OF SOLAR CELLS WHICH WERE RECORDED

TABLE 6. ELECTRICAL CHARACTERISTICS OF CELLS BEFORE AND AFTER CLEANING[(a)]

Cell Characteristics	Cell #022		Cell #029		Cell #036		Cell #041		Cell #064	
	Initially	After Cleaning	Initially	After Cleaning	Initially	After Cleaning	Initially	After Cleaning	Initially	After Cleaning
Open circuit voltage, V	0.560	0.572	0.564	0.562	0.535	0.551	0.536	0.519	0.544	0.544
Short circuit current, mA	581	585	550	553	607	608	557	557	579	571
Voltage at maximum power, V	0.435	0.445	0.425	0.425	0.385	0.405	0.410	0.395	0.420	0.420
Current at maximum power, mA	495	500	463	465	490	489	463	465	504	499
Power maximum, mW	215	223	197	198	189	198	192	184	212	210
Efficiency, percent	11.9	12.3	10.9	10.9	10.4	10.9	10.1	10.1	11.7	11.6
Fill factor	0.662	0.665	0.634	0.638	0.581	0.591	0.643	0.635	0.672	0.675
Series resistance, ohms	0.189	0.191	0.166	0.191	0.261	0.249	0.163	0.204	0.155	0.112
Shunt resistance, ohms	740	680	415	395	480	445	630	670	----	600

(a) Cells were rinsed and then soaked in ethanol-water (95-5 weight percent) for 5 minutes, rinsed with Freon TE (trichlorotrifluorethane plus 4 percent ethanol) and water, vapor degreased with Freon TE, and vacuum baked at 100 C for 30 minutes.

Interpretation of Cell Parameters in Relationship to Encapsulants

Because they form part of the optical path to the cell, encapsulants can profoundly affect the effective conversion efficiency of the photovoltaic module. Moreover, the service life of the cell is determined in a large measure by the choice of the encapsulant system. The critical measure of the utility of an encapsulant is its effect on the electrical output of the cells initially and after exposure to service environments.

Although some detail questions remain, the general features of the electrical output of a photovoltaic cell are well known. Relationships between some of the cell parameters mentioned previously and the cell I-V curve can be elucidated with respect to internal operations of the cell. In simplified terms, the series resistance, R_s, has the effect shown in Figure 8a. The open-circuit voltage, V_{OC}, is not affected, nor is the output at low voltages. However, the maximum power delivered to the load is decreased, and the current and voltage at maximum power are changed. Because of the presence of recombination centers in the band gap, space-charge recombination currents have the effect shown in Figure 8b. Again, the current at low voltages is not seriously affected, but the open-circuit voltage is decreased. Maximum power is also decreased. Shunting currents can produce the effects shown in Figure 8c. Output current at all voltages is affected, and there is a decrease in V_{OC}. Output curves of real cells usually do not show the degree of separation of these effects as indicated in Figure 8. Several effects can combine to give a variety of curve features.

With this brief background, it is useful to examine more closely how the encapsulant impacts some of the key cell parameters.

Short-Circuit Current, I_{SC}

With regard to the encapsulant top cover, the short-circuit current obviously is limited by how much light of the proper wavelength is allowed to reach the cell. Light can be reflected at any one of the interfaces in the optical path, it can be absorbed in the optical path, or it can be scattered in such a way that it will not be absorbed in the collection zone of the cell. In a common encapsulated-cell configuration, the optical path can consist of a top cover, an adhesive, and the antireflecting (AR) coating of the cell. The amount of light reflected depends upon the index of refraction of the various layers and on their thickness.(3) In this study, some of the encapsulant systems increased I_{SC} over that measured when the cell had only the AR coating applied (unencapsulated). That is, the indices were such that a better optical coupling was obtained. In other cases, I_{SC} decreased.

Clearly, the transmittance of the materials in the optical path also affects I_{SC}. Transmittance is a function of wavelength, and a sensitive one at some wavelength ranges for some polymeric materials. In this program, the normal transmittance was measured for some single materials. In designing the ultimate encapsulation system, the transmittance should be known for combinations of materials in the optical path, and as a function of wavelength. For composite materials especially, the diffuse and specular portions of transmittance should also be known. With such information, the "ideal" junction depth can be determined, or optical characteristics can be tailored to a given junction depth.

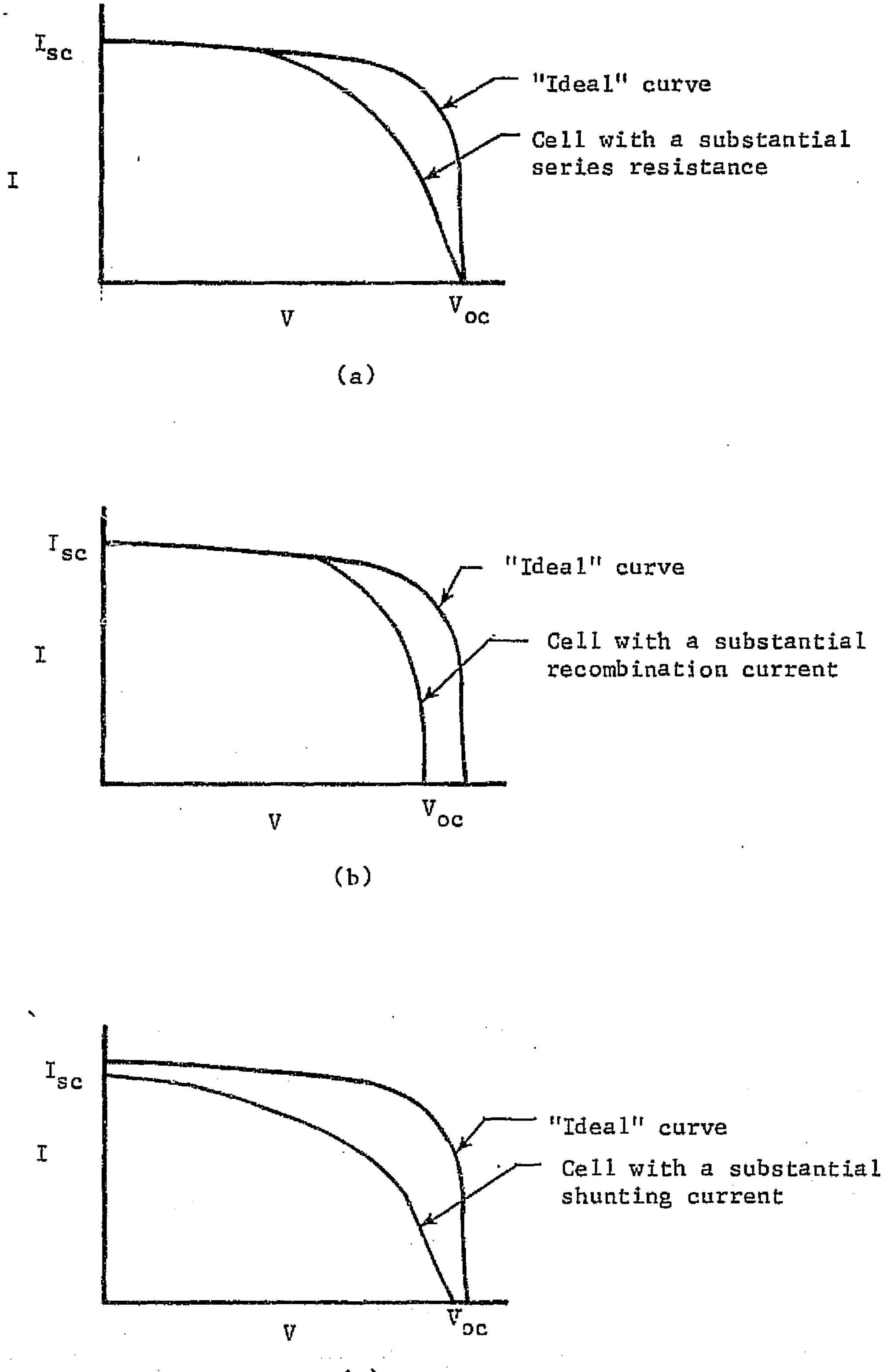

FIGURE 8. SOME RELATIONSHIPS BETWEEN CELL PARAMETERS AND I-V CURVES(2)

Open-Circuit Voltage, V_{oc}

For the ideal silicon cell, the fundamental limitation on V_{oc} is the Schottky diffusion current. V_{oc} is then a function of I_{sc}, the dark current, and temperature. Encapsulants might affect the junction temperature and the junction "perfection factor", A_o.(1) They also can change the surface recombination velocity and space-charge recombination current, thereby affecting V_{oc}.

Series Resistance, R_s

An important effect the encapsulant has on the cell output is the protection, or lack of it, that the encapsulant system gives to the collecting metal grid. Grid corrosion and weakening of the metallization bond can lead to increased R_s. If the encapsulant element (adhesive, for example) interacts excessively with the AR coating-silicon interface, the collection efficiency of the junction can be decreased.

Shunt Resistance, R_{sh}

Shunting current also can be increased within the area of the cell if the interaction of the encapsulant component is excessive. In the absence of high-temperature processes involved in the application of the encapsulant elements, the principal source of a change in shunting current is probably the degree to which the encapsulant passivates the exposed junction around the edge of the conventional cell. It is likely that the shunting currents can be decreased by encapsulation, which, of course, would lead to a more efficient cell. The electrical conductivity of the encapsulant can also lead to a change in shunting currents, but the conductivity, per se, is not likely a large factor in the results to be given subsequently. However, keeping water vapor away from the junction edge is, of course, an advantage.

Measurement of Materials Properties

In this section, the property measurements made on individual materials and combinations of materials are described, and the test cabinets used to expose these materials as well as the encapsulated cells are identified. Included were normal light transmittance measurements, moisture barrier property evaluations, and bond tests. These were made on "as-received" or "as-prepared" samples and following exposures to ultraviolet (UV) irradiation, thermal cycling, high humidity, and high temperature. The test methods and environmental exposures employed in this study are described, together with pertinent equipment and instruments identification.

Light Transmittance Measurements

A Cary Model 14M spectrophotometer equipped with a Model-D lamp power supply was used to measure normal optical transmittances of selected cover film (sheet) materials, of free adhesive films, and of materials subsystems. Optical characterizations were performed before and after exposures to specific weathering environments. Where adhesives were used in combination with the film (sheet) materials, the latter were precleaned with methyl ethyl ketone (MEK) or hexane. Adhesive application was made by brushing where solvent attack on the film (sheet) was not a problem. Where such a problem existed, preformed free films of the adhesives were used. The free films were prepared by wet casting onto a release paper followed by a preapplication solvent-evaporation step.

Film (sheet) specimens with adhesive applied were cured at room temperature, where required, prior to environmental exposures. For exposures, samples were mounted on 7.6 x 22.9 cm (3 x 9 in.) aluminum panels using 3M Magic Mending Tape (No. 810). Following exposures, samples 2.5 x 5 cm (1 x 2 in.) were prepared for use in the Cary. Normal transmittances (optical densities) were determined over the frequency range from 300 to 1200 nm.

Moisture-Barrier Properties

Water-vapor-transmission-rate (WVTR) measurements were made on film (sheet) materials according to ASTM E96-66, using a Vapometer (Thwing-Albert Instrument Company). The Vapometer is a cup 6.4 cm (2.5 in.) in diameter and 5.1 cm (2.0 in.) deep. A circular disc of the film or sheet material, measuring 7.6 cm (3.0 in.) in diameter, was held in place on the cup by a retaining ring and setscrews. Fifty grams of Drierite was used inside each cup. Total exposed film (sheet) area was 0.0032 m^2. Test temperature was 23 C, and outside the cup the relative humidity was maintained at 95 percent.

The measurement of the rate of water-vapor transmission through film/adhesives was accomplished through the use of a film pouch (or "pillow pack"). Figure 9 shows a schematic of one half of the pouch. As indicated, two square films, 8.9 cm (3.5 in.) on a side, were bonded together along the outside edges of the films. The bond area was 1.27 cm (0.50 in.) wide; the total bonded area was 38.7 cm^2 (6.0 $in.^2$). WVTR calculations are based on the film area encompassing the desiccant, 81 cm^2 (12.5 $in.^2$). Pouches were prepared by bonding three sides, inserting the desiccant (10 grams of Drierite), and finally sealing the fourth side. Exposure to UV and temperature cycling was conducted prior to inserting the desiccant and sealing off the fourth side.

A box-type container was employed to determine the rate of water-vapor transmission through the rigid sheet/adhesives. A schematic drawing of this arrangement is shown in Figure 10. The top and bottom of the container were pieces of sheet material 6.4 cm (2.5 in.) square. Two "picture frame" center sections were made with the same overall size as the top and bottom pieces. Each picture frame was 1.27 cm (0.50 in.) wide. When assembled, a cavity 3.8 cm (1.5 in.) square by 0.64 cm (0.25 in.) deep was formed that would hold 10 grams of desiccant. Water-vapor-transmission-rate calculations are based on the total sheet area encompassing the desiccant, 29 cm^2 (4.5 $in.^2$). Exposure to UV and temperature cycling was performed before adding the desiccant and bonding the top sheet to the assembly.

Following preparation, the film pouches and sheet containers were placed in a closed 23 C environment in which the relative humidity, exterior to the samples, was maintained at 95 percent. Periodically, test samples were removed and weighed. Data from successive weighings against elapsed time were plotted. The slope of the resulting straight-line plot defined the WVTR.

Adhesive-Bond Tests

Tests of the adhesive bonds were performed using a modification of ASTM D1002-72. Although numerous bond test methods have been investigated, none is universally applicable nor

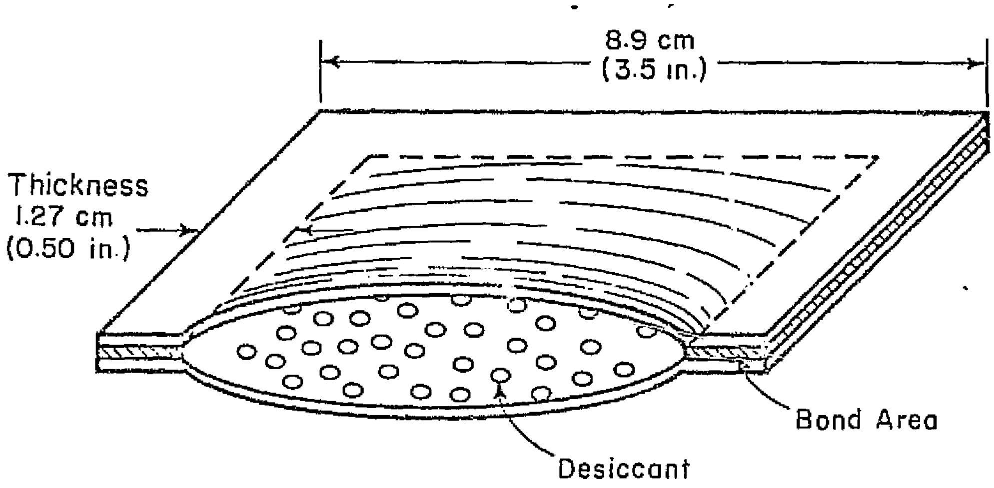

FIGURE 9. SCHEMATIC OF FILM POUCH (PILLOW PACK) USED IN DETERMINING WATER-VAPOR TRANSMISSION THROUGH FILM/ADHESIVE SUBSYSTEMS

(Drawing shows one half of square pouch.)

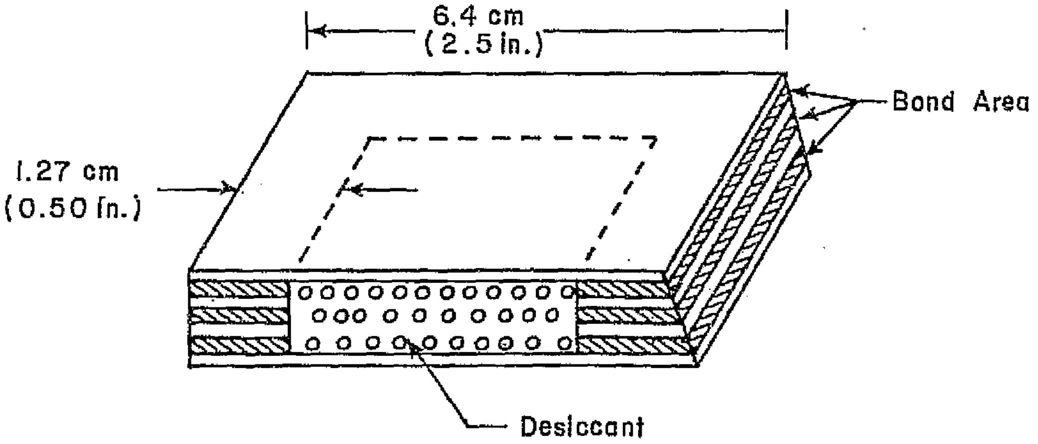

FIGURE 10. SCHEMATIC OF BOX-TYPE CONTAINER USED IN DETERMINING WATER-VAPOR TRANSMISSION THROUGH SHEET/ADHESIVE SUBSYSTEMS

(Drawing shows one half of square container.)

accepted. For the screening evaluations of this study, this test appeared useful and cost effective. However, it should be noted that data suitable for design purposes are not obtained. Specimens were prepared by cutting two 2.5 x 12.7-cm (1 x 5-in.) strips of film on a TMI Precision Paper Cutter. An area of approximately 6 cm^2 on each was marked off for adhesive application. The film areas to be bonded were cleaned with either hexane or MEK. Adhesive was applied to each by brushing on a uniform layer; assembly was carried out according to adhesive manufacturers' suggestion. Most specimens were assembled within a 2- to 3-minute time period after adhesive application. Some, however, required longer drying periods for removal of solvent from the adhesive or curing agent.

For bonding with nonstructural adhesives, a 2.0-kg (4.5-lb) rubber-covered roller (Pressure Sensitive Tape Council, Glenview, Illinois) was used to apply pressure to the bonded area. For structural adhesive specimens, assembly was made by contacting the two specimens and exerting only sufficient pressure (with the fingers) to insure good wetting of the film substrates. Adhesives were cured or conditioned for 3 to 5 days, depending on adhesive type, followed by a 4-hour heat treatment at 50 C. For environmental exposures, specimens were mounted on aluminum panels as described earlier.

Four types of controls were used in this study. Included were unexposed specimens and specimens exposed to 45 C, to 58 C, and to 90 C. Humidity was not controlled in the forced-air ovens used for the thermal controls.

After exposures, bond-strength measurements were performed using a table model Instron Tester at a jaw separation speed of 0.5 cm/min (0.2 in./min). Three specimens were measured for each specimen type evaluated. For thermal controls, only one or two samples were used for each temperature. The reported values are those representative of the highest load that was applied before adhesive or cohesive failure or film breakage or elongation took place.

Environmental Exposures

Four types of environmental exposures were used in this program. These were ultraviolet radiation, thermal cycling, high humidity, and isothermal aging at elevated temperature. The UV exposures were carried out in either a xenon lamp Weather-O-Meter, Atlas Model 60W, or a carbon arc Weather-O-Meter, Atlas Model XW-R. Thermal cycling from -40 to +90 C at a 6 cycles/day rate was performed in a Webber cabinet (Model No. WF-6-125-300). High-humidity exposures (100 percent R.H. and 38 C) were carried out in a Precision Scientific Company (Army-Navy Aeronautical-Spec. AN-H-31) cabinet. High-temperature aging treatments were performed in a conventional air-circulating oven. Cell-parameter and materials-property measurements were made before and after the different environmental exposures.

PHASE I. RESULTS AND DISCUSSION OF INITIAL SCREENING EVALUATIONS OF ENCAPSULATION MATERIALS AND ENCAPSULATED CELLS

Summarized in this section are the results of the initial screening (Phase I) evaluations of presently available, candidate encapsulation materials, combinations of materials and their interactions/interfaces, and encapsulated cells representing the selected encapsulation-system designs and materials described earlier. Comments are made about the results and the behavior of the various materials in the aging environments described previously. The first part of this section gives the results for "total polymeric systems" (all of the encapsulation components are polymers). The results for systems employing glasses as the top cover, and in some cases also as the substrate, are discussed next.

Results for Total Polymer Encapsulation Systems

Light Transmittance Evaluations

Values of normal light transmittance were obtained in the Cary instrument at 100-nm increments over the range 300 to 1200 nm for selected film, sheet, adhesive, and adhesive/film or sheet combinations, before and after exposure to specific weather environments. The performance of materials has been characterized by comparing transmittances before and after exposure and computing values of R as defined by the equation:

$$R = \frac{T_{\text{exposed}}}{T_{\text{unexposed}}} ,$$

where T is the transmittance. Generally, R values are reported for the wavelength range 300 to 700 nm, the range 700 to 1200 nm, and the total range 300 to 1200 nm. These values are designated R_{VIS}, R_{IR}, and R_T, respectively. For each range, the transmittance was incrementally integrated at 100-nm intervals.

Optical Performance of Film and Sheet Cover Materials. For selected film and sheet cover candidates, the effects of individual exposures to UV, thermal cycling, and high humidity on normal light transmittance were determined. The data (summarized in Table 7) indicate that the materials generally are not significantly affected by either UV or thermal cycling. The transmittance of Sun-Lite sheet appears to decrease somewhat after thermal cycling (R_T = 0.88).

High-humidity exposure appears to affect the optical properties of Korad A films, particularly in the IR range. The films turn milky after several hours of exposure, with a resultant R_T value of 0.91. All other film and sheet candidates were not markedly affected by the high-humidity exposure.

Optical Performance of Film- and Sheet-to-Adhesives Combinations. Film and sheet total encapsulant designs will contain a combination of a film or a sheet and an adhesive above the silicon cell. This combination will constitute the material path that must be traversed by light incident on the array. To examine the effect of weathering environments on such subsystems, combinations of film or sheet and adhesive, or three plies of these materials in which the adhesive

TABLE 7. TRANSMITTANCE RATIOS(a) OF ENVIRONMENTALLY EXPOSED FILM AND SHEET COVER CANDIDATES

Film or Sheet Material (Thickness)	Exposure Type(b)	Exposure Time, hr	R_T	R_{IR}	R_{VIS}
Tedlar (102 μm)	none	—	—	—	—
	UV	1002	0.98	0.97	1.00
	TC	1009	0.94	0.94	0.95
	HH	500	0.96	0.96	0.97
Korad A (152 μm)	none	—	—	—	—
	UV	1002	0.99	0.99	1.00
	TC	1012	0.99	0.97	1.02
	HH	500	0.91	0.94	0.87
Tuffak (508 μm)	none	—	—	—	—
	UV	1001	0.99	1.00	0.98
	TC	1176	0.97	0.94	0.99
	HH	500	0.98	0.97	0.99
Mylar (178 μm)	none	—	—	—	—
	UV	1034	0.99	0.97	1.02
	TC	1032	0.97	0.98	0.96
	HH	—	—	—	—
"Teflon" FEP (127 μm)	none	—	—	—	—
	UV	1034	1.00	0.99	1.00
	TC	1133	0.98	0.98	0.98
	HH	500	0.97	0.98	0.95
Halar (127 μm)	none	—	—	—	—
	UV	490	0.98	0.98	0.97
	TC	500	0.96	0.96	0.97
	HH	500	1.00	0.99	1.02
Sun-Lite (635 μm)	none	—	—	—	—
	UV	490	1.23	1.37	1.09
	TC	500	0.88	0.93	0.83
	HH	500	1.11	1.10	1.11

(a) Transmittance ratios, designated R_T, R_{IR}, and R_{VIS}, are the ratios of normal light transmittance of exposed to that of unexposed samples over the ranges 300 to 1200 nm, 700 to 1200 nm, and 300 to 700 nm, respectively. Ratios were computed from measurements on single samples.

(b) UV, TC, and HH designate ultraviolet radiation (xenon lamp), thermal-cycling, and high-humidity exposures, respectively.

is the inner layer of the sandwich, were subjected to light-transmittance measurements with R-value computations as above.

Transmittance data for a number of selected adhesives with the major cover film and sheet materials are listed in Tables 8 through 14. In several cases, free films of the adhesives were cast and subjected to the same environmental aging.

Scotch-Weld 2216 B/A. Data obtained for various cover candidates with Scotch-Weld B/A, a moderately flexible, structural epoxy, are presented in Table 8. Note that three types of specimens are included: a "free" film of the adhesive, a film (or sheet)/adhesive combination, and a film/adhesive/film (or sheet) sandwich. The adhesive alone and the film/adhesive specimens were exposed to the various environments for approximately 500 hours; the sandwiches were exposed for approximately 1000 hours. With the free film, only the high-humidity exposure seriously affected the transmittance.

Exposure of the film/adhesive combinations to high humidity gave rather curious results. The transmittance is of course affected by the presence of interfaces and absorption in the elements, and thus some variance in the results with the various films could be expected. However, the size of the variance is rather unexpected. Note that with Sun-Lite and Korad A the reduction in transmittance was large, while the reduction was comparatively much lower with Tuffak, "Teflon" FEP, Tedlar, and Halar. The explanation for such results is not clear; they may be due to the type of interaction between the adhesive and film.

Exposure to UV did not seriously affect the transmittance of any of the specimens, but it must be remembered that the UV exposure time is extremely short compared with 20 years. The thermal-cycle exposure likewise did not produce large effects. The large ratios for Sun-Lite after UV exposure are as yet unexplainable.

Acryloid B-7. Exposures to high humidity for 500 hours reduced the optical transmittance of free films of Acryloid B-7 significantly (Table 9). When the adhesive was evaluated in combination with a number of film (sheet) materials, only combinations with Tedlar and Halar maintained good light transmittances after the same level of high-humidity exposure.

Generally speaking, all subsystems except those involving Sun-Lite sheet maintained stable transmittance after 500 hours of UV exposure. The Sun-Lite subsystem and, to a lesser extent, the Tuffak and "Teflon" FEP subsystems were adversely affected by thermal cyclings of 500 hours.

Silgrip SR-573. This silicon resin adhesive can be used directly as a thermoplastic laminating adhesive or can be cured with an amine or peroxide catalyst to provide increased thermal stability. Exposure to high humidity for 500 hours reduced the optical transmittance levels of Korad A, Halar, and Sun-Lite in combination with the uncatalyzed adhesive. The R_T values obtained for these subsystems were 0.54, 0.69, and 0.51, respectively (Table 10).

It appears that under certain conditions Silgrip SR-573 continues to cure in the presence of catalyst when exposed to elevated temperatures or UV. This suggestion stems from the fact that R_T values much larger than one were obtained. It appears that only Korad A subsystems with SRC-30 catalyzed adhesive are adversely affected by thermal cycling. All subsystems tested held up well to UV exposures of up to 1000 hours.

TABLE 8. TRANSMITTANCE RATIOS[a] OF ENVIRONMENTALLY EXPOSED MATERIALS COMBINATIONS (SUBSYSTEMS) BASED ON SCOTCH-WELD 2216 B/A

Film/Adhesive Materials	Exposure Type[b]	Exposure Time, hr	R_T	R_{IR}	R_{VIS}
Scotch-Weld 2216 B/A Clear[c]	none	--			
ditto	U.V.	490	1.08	1.05	1.14
"	T.C.	500	1.00	0.99	1.02
"	H.H.	500	0.72	0.74	0.69
Sun-Lite/2216 [d]	none	--			
ditto	U.V.	490	1.45	1.50	1.38
"	T.C.	500	0.70	0.69	0.73
"	H.H.	500	0.54	0.65	0.41
Tuffak/2216	none	--			
ditto	U.V.	490	1.01	1.00	1.02
"	T.C.	500	0.98	0.99	0.97
"	H.H.	500	1.05	1.05	1.05
Tuffak/2216/Tuffak	none	--			
ditto	U.V.	1001	1.13	1.10	1.18
"	T.C.	1176	1.10	1.07	1.13
"	58C	1001	1.05	0.97	1.17
"	90C	1001	1.01	0.98	1.05
"Teflon" FEP/2216	none	--			
ditto	U.V.	490	0.85	0.85	0.86
"	T.C.	500	0.91	0.95	0.86
"	H.H.	500	1.01	1.04	0.96
"Teflon" FEP/2216/ "Teflon" FEP	none	--			
ditto	U.V.	1001	1.03	1.05	1.01
"	T.C.	1034	1.06	1.05	1.08
"	58C	1001	0.99	1.01	0.97
"	90C	1001	1.01	1.06	0.95
Korad A/2216	none	--			
ditto	U.V.	490	1.01	1.00	1.01
"	T.C.	500	0.87	0.88	0.85
"	H.H.	500	0.48	0.62	0.26
Korad A/2216/Korad A	none	--			
ditto	U.V.	1002	1.11	1.13	1.08
"	T.C.	1012	1.09	1.09	1.10
"	58C	1001			
"	90C	1001			

TABLE 8. (Continued)

Film/Adhesive Materials	Exposure Type(b)	Exposure Time, hr	R_T	R_{IR}	R_{VIS}
Tedlar/2216	none	--			
ditto	U.V.	490	1.04	1.00	1.08
"	T.C.	500	0.94	0.96	0.90
"	H.H.	500	0.85	0.90	0.77
Tedlar/2216/Tedlar	none	--			
ditto	U.V.	1002	1.22	1.20	0.24
"	T.C.	1009	1.01	1.05	0.93
Halar/2216	none	--			
ditto	U.V.	490	1.02	1.04	0.98
"	T.C.	500	0.88	0.94	0.79
"	H.H.	500	0.96	0.98	0.94

(a) Transmittance ratios, designated R_T, R_{IR}, and R_{VIS}, are the ratios of normal light transmittance of exposed to that of unexposed samples over the ranges 300 to 1200 nm, 700 to 1200 nm, and 300 to 700 nm, respectively. Ratios were computed from measurements on single samples.

(b) UV, TC, and HH designate ultraviolet radiation (xenon lamp), thermal-cycling, and high-humidity exposures, respectively.

(c) Adhesive alone; no film or sheet material.

(d) Abbreviated form designates the Scotch-Weld 2216 B/A clear.

TABLE 9. TRANSMITTANCE RATIOS[a] OF ENVIRONMENTALLY EXPOSED MATERIALS COMBINATIONS (SUBSYSTEMS) BASED ON ACRYLOID B-7

Film/Adhesive Materials	Exposure Type[b]	Exposure Time, hr	R_T	R_{IR}	R_{VIS}
Acryloid B-7 Adhesive[c]	none	--			
ditto	U.V.	490	1.28	1.13	1.50
"	T.C.	500	1.09	1.01	1.22
"	H.H.	500	0.47	0.50	0.42
Korad A/Acryloid B-7	none	--			
ditto	U.V.	490	1.04	1.04	1.03
"	T.C.	500	1.04	1.06	1.01
"	H.H.	500	0.70	0.78	0.57
Halar/Acryloid B-7	none	--			
ditto	U.V.	490	0.95	0.97	0.94
"	T.C.	500	1.02	1.04	0.99
"	H.H.	500	1.02	1.01	1.02
Tedlar/Acryloid B-7	none	--			
ditto	U.V.	490	1.04	1.03	1.04
"	T.C.	500	0.98	0.99	0.97
"	H.H.	500	1.00	0.98	1.02
"Teflon" FEP/Acryloid B-7	none	--			
ditto	U.N.	490	0.94	0.93	0.96
"	T.C.	500	0.93	0.94	0.93
"	H.H.	500	0.69	0.76	0.61
Tuffak/Acryloid B-7	none	--			
ditto	U.N.	490	1.04	1.02	1.06
"	T.C.	500	0.86	0.79	0.93
"	H.H.	500	0.68	0.69	0.67
Sun-Lite/Acryloid B-7	none	--			
ditto	U.V.	490	0.84	0.87	0.80
"	T.C.	500	0.74	0.74	0.74
"	H.H.	500	0.31	0.31	0.31

(a) Transmittance ratios, designated R_T, R_{IR}, and R_{VIS}, are the ratios of normal light transmittance of exposed to that of unexposed samples over the ranges 300 to 1200 nm, 700 to 1200 nm, and 300 to 700 nm, respectively. Ratios were computed from measurements on single samples.

(b) UV, TC, and HH designate ultraviolet radiation (xenon lamp), thermal-cycling, and high-humidity exposures, respectively.

(c) Adhesive alone; no film or sheet material.

TABLE 10. TRANSMITTANCE RATIOS(a) OF ENVIRONMENTALLY EXPOSED MATERIALS COMBINATIONS (SUBSYSTEMS) BASED ON SILGRIP SR-573

Film/Adhesive Materials Combinations	Exposure Type(b)	Exposure Time, hr	R_T	R_{IR}	R_{VIS}
Korad A/Silgrip SR-573	none	--			
ditto	U.V.	490	1.01	1.02	1.00
"	T.C.	500	1.18	1.14	1.27
"	H.H.	500	0.54	0.55	0.52
Korad A/Silgrip SR-573(c)/ Korad A	none	--			
ditto	U.V.	1002	0.98	0.94	1.07
"	T.C.	1012	0.83	0.75	0.99
Halar/Silgrip SR-573	none	--			
ditto	U.V.	490	1.04	1.09	0.98
"	T.C.	500	0.98	1.11	0.85
"	H.H.	500	0.69	0.78	0.58
Tedlar/Silgrip SR-573	none	--			
ditto	U.V.	490	1.10	1.10	1.11
"	T.C.	500	0.94	1.00	0.88
Tedlar/Silgrip SR-573(c)/ Tedlar	none	--			
ditto	U.V.	1002	0.95	1.06	0.75
"	T.C.	1009	1.63	1.64	1.61
"Teflon" FEP/Silgrip SR-573	none	--			
ditto	U.V.	490	0.94	1.00	0.87
"	T.C.	500	0.65	0.70	0 60
"	H.H.	500	0.87	0.88	0.86
"Teflon" FEP/Silgrip SR-573(d)/"Teflon" FEP	none	--			
ditto	U.V.	1046	1.79	1.74	1.87
"	T.C.	1133	1.49	1.52	1.45
"	58C	1001	1.38	1.45	1.30
"	90C	1001	1.04	1.00	1.09
Lexan-Silgrip SR-573	none	--			
ditto	U.V.	490	1.07	1.09	1.06
"	T.C.	500	1.14	1.15	1.13
"	H.H.	500	0.96	0.99	0.93

TABLE 10. (Continued)

Film/Adhesive Materials Combinations	Exposure Type(b)	Exposure Time, hr	R_T	R_{IR}	R_{VIS}
Lexan-Silgrip SR-573(d)/ Lexan	none	--			
ditto	U.V.	1001	1.81	1.91	1.69
"	T.C.	1176	2.16	2.25	2.06
"	58C	1001	1.18	1.17	1.19
"	90C	1001	1.61	1.46	1.82
Mylar-Silgrip SR-573(d)/ Mylar	none	--			
ditto	U.V.	1034	1.09	1.11	1.06
"	T.C.	1032	2.55	2.19	3.46
"	58C	1001	2.80	2.49	3.57
"	90C	1001	2.61	2.27	3.46
Sun-Lite-Silgrip SR-573	none	--			
ditto	U.V.	490	1.47	1.64	1.30
"	T.C.	500	1.36	1.31	1.41
"	H.H.	500	0.51	0.57	0.45

(a) Transmittance ratios, designated R_T, R_{IR}, and R_{VIS}, are the ratios of normal light transmittance of exposed to that of unexposed samples over the ranges 300 to 1200 nm, 700 to 1200 nm, and 300 to 700 nm, respectively. Ratios were computed from measurements on single samples.

(b) UV, TC, and HH designate ultraviolet radiation (xenon lamp), thermal-cycling, and high-humidity exposures, respectively.

(c) Silgrip adhesive catalyzed with SRC-30, a peroxide catalyst.

(d) Silgrip adhesive catalyzed with 1.5 percent benzoyl peroxide.

Silastic 732 RTV. This elastomeric silicone is cured by atmospheric moisture. It was examined in combinations with films of "Teflon" FEP, Korad A, and Tedlar (Table 11). Of the three, the "Teflon" FEP subsystem appeared to perform best over the different environmental exposures. However, decreases in transmittance were observed with these subsystems following thermal cycling, especially in the 300 to 700-nm range. The Tedlar subsystems generally were somewhat more affected than the "Teflon" FEP by the different environments. The Korad A subsystem generally performed more poorly, with the transmittances being reduced markedly by aging at both 58 and 90 C. Interestingly, the thermally cycled Korad A subsystem held up reasonably well.

RTV 118. This elastomeric silicon was evaluated only in subsystems with "Teflon" FEP and Mylar (Table 12). The light transmittance of the "Teflon" FEP subsystem decreased substantially after thermal cycling ($R_T = 0.76$), while the Mylar subsystem decreased markedly after UV exposure ($R = 0.60$). Optical performance was unaffected or slightly improved for specimens of both subsystems exposed to the other environments.

Cavalon 3100S. This thermosetting acrylic, reacted with one of three activators (3300S, 3303S, or benzoyl peroxide), was evaluated in subsystems with "Teflon" FEP, Mylar, and Tedlar films. The adhesive system using activators 3300S and 3303S darkened in color on exposure to both UV and heat. No appreciable initial color was observed with benzoyl peroxide, but unreacted peroxide produced opaqueness.

Optical transmittance data are presented in Table 13. It should be noted that the Tedlar-Cavalon 3100S (5% benzoyl peroxide) subsystem improved in optical transmittance following exposure to UV, thermal cycling, or thermal aging. This is probably due to the fact that benzoyl peroxide cure is accelerated by either UV or heat and initial opaqueness of the adhesive film clears as the cross-linking reaction proceeds. If an appropriate combination of cure conditions could be established, it is possible that this adhesive may be practical for solar-cell-cover applications. Cure will be governed by the temperature and time required and the heat-distortion characteristics of the cover material used. As it is, this adhesive still may be of interest for encapsulant bonding applications where optical clarity is not important.

Scotch-Grip 4693, Scotch-Grip 4475, and Scotch-Weld 3520 B/A. These adhesives have been studied only in single subsystems in the current program (Table 14). Scotch-Grip 4693 and Scotch-Grip 4475 normally are used to bond plastic materials. Scotch-Grip 4693 did not perform well in combination with Korad A. After thermal aging at 90 C for approximately 1000 hours, an R_T value of 0.47 was obtained. Scotch-Grip 4475 has a low softening point. In subsystems with Korad A, partial delamination and adhesive darkening occurred during both thermal cycling and 90 C thermal aging exposures.

Scotch-Weld 3520 B/A is a structural epoxy. Subsystems with Mylar maintained good optical transmittance after exposures to UV, thermal cycling, and thermal aging. Studies of other subsystems containing 3520 appear warranted.

TABLE 11. TRANSMITTANCE RATIOS(a) OF ENVIRONMENTALLY EXPOSED MATERIALS COMBINATIONS (SUBSYSTEMS) BASED ON SILASTIC 732 RTV

Film/Adhesive Materials Combinations	Exposure Type(b)	Exposure Time, hr	R_T	R_{IR}	R_{VIS}
"Teflon" FEP/Silastic 732 RTV/"Teflon" FEP	none	--			
ditto	U.V.	1046	1.13	1.12	1.14
"	T.C.	1133	0.75	0.80	0.69
"	58C	1001	1.20	1.18	1.23
"	90C	1001	1.07	1.04	1.11
Korad A/Silastic 732 RTV/ Korad A	none	--			
ditto	U.V.	1002	0.86	0.86	0.88
"	T.C.	1012	0.87	0.92	0.78
"	58C	1028	0.62	0.75	0.47
"	90C	1028	0.52	0.62	0.39
Tedlar/Silastic 732 RTV/ Tedlar	none	--			
ditto	U.V.	1002	0.88	0.93	0.83
"	T.C.	1009	0.88	0.97	0.76
"	58C	1028	0.85	0.91	0.77
"	90C	1028	0.88	0.92	0.82

(a) Transmittance ratios, designated R_T, R_{IR}, and R_{VIS}, are the ratios of normal light transmittance of exposed to that of unexposed samples over the ranges 300 to 1200 nm, 700 to 1200 nm, and 300 to 700 nm, respectively. Ratios were computed from measurements on single samples.

(b) UV, TC, and HH designate ultraviolet radiation (xenon lamp), thermal-cycling, and high-humidity exposures, respectively.

TABLE 12. TRANSMITTANCE RATIOS(a) OF ENVIRONMENTALLY EXPOSED MATERIALS COMBINATIONS (SUBSYSTEMS) BASED ON RTV 118

Film /Adhesive Materials Combinations	Exposure Type(b)	Exposure Time, hr	R_T	R_{IR}	R_{VIS}
"Teflon" FEP/RTV 118/ "Teflon" FEP	none	--			
ditto	U.V.	1034	1.08	1.06	1.12
"	T.C.	1133	0.76	0.78	0.74
"	58C	1001	1.17	1.13	1.22
"	90C	1001	1.15	1.10	1.23
Mylar/RTV 118/Mylar	none	--			
ditto	U.V.	1034	0.60	0.63	0.54
"	T.C.	1133	1.23	1.31	1.13
"	58C	1001	1.01	1.14	0.85
"	90C	1001	1.11	1.28	0.90

(a) Transmittance ratios, designated R_T, R_{IR}, and R_{VIS}, are the ratios of normal light transmittance of exposed to that of unexposed samples over the ranges 300 to 1200 nm, 700 to 1200 nm, and 300 to 700 nm, respectively. Ratios were computed from measurements on single samples.

(b) UV, TC, and HH designate ultraviolet radiation (xenon lamp), thermal-cycling, and high-humidity exposures, respectively.

TABLE 13. TRANSMITTANCE RATIOS[(a)] OF ENVIRONMENTALLY EXPOSED MATERIALS COMBINATIONS (SUBSYSTEMS) BASED ON CAVALON 3100S

Film/Adhesive Materials Combinations	Exposure Type[(b)]	Exposure Time, hr	R_T	R_{IR}	R_{VIS}
"Teflon" FEP/Cavalon 3100S (Activator 3300S)/"Teflon" FEP	none	--			
ditto	U.V.	1001	0.95	1.01	0.82
"	T.C.	1133	0.87	1.09	0.41
"	58C	1001	1.46	1.43	1.53
"	90C	1001	0.98	1.18	0.57
Mylar/Cavalon 3100S (Activator 3300S)/Mylar	none	--			
ditto	U.V.	1034	1.03	1.13	0.87
"	T.C.	1032	1.10	0.87	1.02
"	58C	1001	1.16	1.25	1.02
"	90C	1001	0.84	0.98	0.62
Tedlar/Cavalon 3100S (Activator 3303S)/Tedlar	none				
ditto	U.V.	1002	0.61	0.67	0.51
"	T.C.	1009	1.07	1.12	0.99
"	58C	1028	0.69	0.81	0.53
"	90C	1028	0.61	0.78	0.39
Tedlar/Cavalon 3100S (5% benzoyl peroxide/ Tedlar	none	--			
ditto	U.V.	1002	1.76	1.89	1.57
"	T.C.	1009	1.47	1.54	1.37
"	58C	1028	1.67	1.93	1.29
"	90C	1028	2.19	1.93	2.58

(a) Transmittance ratios, designated R_T, R_{IR}, and R_{VIS}, are the ratios of normal light transmittance of exposed to that of unexposed samples over the ranges 300 to 1200 nm, 700 to 1200 nm, and 300 to 700 nm, respectively. Ratios were computed from measurements on single samples.

(b) UV, TC, and HH designate ultraviolet radiation (xenon lamp), thermal-cycling, and high-humidity exposures, respectively.

TABLE 14. TRANSMITTANCE RATIOS[(a)] OF ENVIRONMENTALLY EXPOSED MATERIALS COMBINATIONS (SUBSYSTEMS) BASED ON SCOTCH-GRIP 4693, SCOTCH-GRIP 4475, AND SCOTCH-WELD 3520 B/A

Film/Adhesive Materials Combinations	Exposure Type[(b)]	Exposure Time, hr	R_T	R_{IR}	R_{VIS}
Korad A/Scotch-Grip 4693/ Korad A	none	--			
ditto	U.V.	1002	0.97	1.01	0.89
"	T.C.	1012	1.26	1.27	1.25
"	58C	1028	0.68	0.78	0.55
"	90C	1028	0.47	0.57	0.36
Korad A/Scotch-Grip 4475/ Korad A	none	--			
ditto	U.V.	1002	1.09	1.13	1.03
"	T.C.	1012	0.47	0.56	0.29
"	58C	1028	0.36	0.45	0.24
"	90C	1028	0.13	0.20	0.04
Mylar/Scotch-Weld 3520 B/A/Mylar	none	--			
ditto	U.V.	1034	1.14	1.17	1.11
"	T.C.	1032	1.26	1.33	1.16
"	58C	1001	1.22	1.34	1.06
"	90C	1001	1.23	1.35	1.06

(a) Transmittance ratios, designated R_T, R_{IR}, and R_{VIS}, are the ratios of normal light transmittance of exposed to that of unexposed samples over the ranges 300 to 1200 nm, 700 to 1200 nm, and 300 to 700 nm, respectively. Ratios were computed from measurements on single samples.

(b) UV, TC, and HH designate ultraviolet radiation (xenon lamp), thermal-cycling, and high-humidity exposures, respectively.

Moisture-Barrier-Property Evaluations

Barrier Performance of Film and Sheet Materials. Water-vapor-transmission-rate measurements were made in duplicate for a number of film and sheet cover candidates using the technique described earlier. Measurements were made on unexposed samples and on samples subjected to UV radiation using a carbon arc and to temperature cycling. The data are summarized in Table 15. These were the only carbon-arc UV exposures used in this program and were employed on the basis of equipment availability; all others were xenon-lamp exposures.

Use of the carbon-arc UV source, which contains sizable amounts of radiation in the 240 to 300-nm wavelength range, which is not present in xenon-lamp exposures, had a detrimental effect on most of the materials that were exposed. Only the "Teflon" FEP and Halar films were unaffected, at least visually, by 500-hour exposures. The acrylic materials (Acrylite, Korad A, and Flexigard) yellowed and exhibited surface crazing. The polycarbonates (Lexan sheet and Tuffak), the Sun-Lite sheet, and Tedlar also yellowed. Tedlar also embrittled. Surface blooming, of either an additive or degradation product of the Mylar, occurred and the bulk film became very cloudy.

Examination of the data of Table 15 indicates, interestingly, that the carbon-arc exposure, although having pronounced effects on surface characteristics, generally did not markedly affect barrier characteristics. Only the Halar and, to a lesser extent, the Mylar and Korad A were adversely affected by carbon-arc exposures to 500 hours. The Sun-Lite sample appeared to be improved by the UV exposure, but this may be the result of sample-to-sample variations in filler content. More work is needed with this material.

Thermal-cycling exposures of 500 hours appeared to have little effect on most of the cover candidates. Again, the barrier characteristics of the Halar film were most affected.

Barrier Performance of Film- and Sheet-to-Adhesive Subsystems. Results of WVTR measurements of subsystems of "Teflon" FEP and Mylar with selected adhesives are summarized in Tables 16 and 17, respectively. For studies of "Teflon" FEP, the adhesively bonded pouch was used as a measure of the effectiveness of the adhesive as a moisture-vapor barrier. The best overall performance with "Teflon" FEP was achieved with Scotch-Weld 2216 B/A, Silgrip SR-573, Silgrip SR-574, and Acryloid B-7. However, some bubble formation was observed after temperature cycling with the two Silgrip adhesives.

The Cavalon 3100S (3300S) darkened considerably during both UV and temperature-cycling exposures, and performed somewhat more poorly than other subsystems. However, it was markedly affected by UV. The greatest average increase in WVTR was recorded with the moisture-cured silicone adhesives (RTV-118 and Silastic 732 RTV).

Evaluation of the data obtained with the various Mylar subsystems (Table 17) indicates that, with the exception of the Silastic 732 RTV subsystem, none performed satisfactorily through the UV and temperature-cycling exposures. The Silgrip SR-573, Scotch-Weld 2216 B/A, Acryloid B-7, and Cavalon 3100S adhesives all failed, primarily because of loss of adhesion. Only the Silastic 732 RTV performed well. It is possible that the "pouch" technique may not be satisfactory for determining barrier properties with high-modulus (stiff) film materials. The "bowing" effect created by the desiccant inside the pouch puts a considerable stress on the adhesive bonds. The Silastic 732 RTV, being an elastomeric, apparently was better able to withstand these stresses.

TABLE 15. WATER-VAPOR-BARRIER PROPERTIES(a) OF POLYMERIC FILM AND SHEET COVER CANDIDATES BEFORE AND AFTER ENVIRONMENTAL EXPOSURES

Material	Thickness, µm (mils)	WVTR, g/24 hr/m^2 at 23 C and 95% R.H. (at Indicated Thickness)		
		Unexposed	UV-50(b), 45-58 C	TC-500(b)
Halar	127 (5)	1.07	1.51	2.88
"Teflon" FEP	127 (5)	1.13	1.08	1.21
Lexan	3175 (125)	1.29	1.27	1.31
Acrylite	3175 (125)	2.16	1.67	1.53
Mylar	178 (7)	2.25	2.67	2.17
Sun-Lite	635 (25)	4.37	2.84	3.85
Tedlar	102 (4)	4.70	—	3.85
Tuffak	508 (20)	5.14	5.29	4.86
Flexigard	127 (5)	5.31	5.57	5.34
Korad A	152 (6)	22.81	26.10	23.51

(a) Measurements were performed in duplicate.

(b) UV-500 and TC-500 designate exposures of 500 hours to UV radiation and to thermal cycling, respectively. For these samples a carbon-arc source of UV was used. In all other studies described in this report the UV source was a xenon lamp.

TABLE 16. WATER-VAPOR-BARRIER PROPERTIES[a] OF "TEFLON" FEP (127-μm THICK) FILMS BONDED WITH VARIOUS ADHESIVES BEFORE AND AFTER ENVIRONMENTAL EXPOSURE

	WVTR, g/24 hr/m^2 at 23 C, 95% R.H.		
Adhesive	Unexposed	UV-1000[b], 45-58 C	TC-1000[b]
Silgrip SR-573	0.204	0.258	0.237
Silgrip SR-574	0.250	0.217	0.244
RTV-118	0.224	0.255	0.344
Silastic 732 RTV	0.282	0.401	0.237
Scotch-Weld 2216 B/A	0.201	0.221	0.189
Acryloid B-7	0.273	0.203	0.181
Cavalon 3100S	0.167	0.240	0.216
None (heat sealed)	0.154	0.151	0.162

(a) Measurements were performed in duplicate.

(b) UV-1000 and TC-1000 designate exposures of 1000 hours to UV radiation (xenon lamp) and to thermal cycling, respectively.

TABLE 17. WATER-VAPOR-BARRIER PROPERTIES(a) OF WEATHERABLE MYLAR (178-μm THICK) FILMS BONDED WITH VARIOUS ADHESIVES BEFORE AND AFTER ENVIRONMENTAL EXPOSURE

	WVTR, g/24 hr/m^2 at 23 C, 95% R.H.		
Adhesive	Unexposed	UV-1000(b), 45-58 C	TC-1000(b)
Silgrip SR-573	1.85	2.25	1.90(e)
Silastic 732 RTV	1.77	1.80	1.81
Scotch-Weld 2216 B/A	1.80	1.90	1.85(e)
Acryloid B-7	2.21	(c)	(c)
Cavalon 3100S	1.74	(d)	(d)

(a) Measurements were performed in duplicate.

(b) UV-1000 and TC-1000 designate exposures for 1000 hours to UV radiation (xenon lamp) and to thermal cycling.

(c) Some loss of adhesion was noted.

(d) Some loss of adhesion and darkening were noted.

(e) Single determination. Loss of adhesion of one sample occurred.

The results from studies of the barrier properties of subsystems of the sheet material cover candidates (Acrylite, Lexan, and Sun-Lite) are presented in Table 18. Bubble formation occurred during laminations involving the thermoplastic acrylic adhesive (Acryloid B-7) and the Acrylite and Lexan sheet materials. It is likely that solvent in the adhesive formulation is being absorbed on the surface of these sheet materials and is released to produce bubbles when heat and pressure are applied. A number of failures (high rate of water-vapor transmission depleting the desiccant) were observed in the unexposed and thermal-cycled samples. No bubbles were noted with the Sun-Lite/Acryloid B-7 subsystems.

The Acryloid B-7 and Scotch-Grip 4693 perform better than Silgrip SR-573 with the Sun-Lite material. With the Acrylite and Lexan materials, the Scotch-Grip 4693 and Silgrip SR-573 are superior to Acryloid B-7.

Adhesive-Bond Evaluations

Bond tests of film/adhesive and sheet/adhesive subsystems combinations were carried out to identify, from among the adhesives candidates identified in earlier work(3), those adhesives that are most likely to provide encapsulation systems that are resistant to delamination and other forms of failure during exposures to various hostile weathering environments. In this work lap-shear measurements have been used to index bond strengths. Lap shear was selected primarily on the basis of its relative ease of measurement, since the screening task has dealt with very large numbers of materials combinations. It is recognized, of course, that other methods of evaluating adhesive bonds using various types of stress, e.g., tensile, shear, etc., could also have been used to provide information in characterizing the bond, as noted in the experimental procedures section of the report.

Throughout the discussion that follows, summary tables of the bond-strength data are provided; these have been condensed from original detailed tabulations of the data. Bonding characteristics of six candidate film covers with selected adhesives were studied before and after environmental exposures. All samples were preconditioned by storage at 23 C and 50 percent relative humidity for 12 to 24 hours prior to testing. Environmental exposures included UV radiation, thermal cycling, and isothermal aging at 45, 58, and 90 C.

Bonding to "Teflon" FEP Film. The relative strengths of adhesive bonds formed between "Teflon" FEP (127-μm thick) and five adhesives candidates were determined before and after environmental exposures using the lap-shear method. These data are summarized in Table 19. They reveal that the predominant failure mode is film elongation outside the bond area at a load of approximately 6.2×10^4 N/m^2 (9 psi), independent of exposure. Only the Silastic 732 RTV system produced any failures of the cohesive or adhesive type at a load less than that required for film elongation. Thus, generally speaking, the yield strength of the "Teflon" FEP film defines the load limit that can be applied to these subsystems if tensile and shear forces of the type present in the lap-shear test are representative of those that might be experienced by the encapsulant. Cavalon 3100S with Activator 3300S provides a bond strength in excess of film yield strength, but discolors when exposed to UV or heat. The limitations of Silastic 732 RTV with "Teflon" FEP were mentioned above. Thus, the Scotch-Weld 2216 B/A appears to be the best structural adhesive for this application, while both RTV 118 and Silgrip SR-573 (cured with 1.5% benzoyl peroxide) are satisfactory nonstructural adhesives. The RTV 118 would be most applicable if an elastomeric is desirable, while the Silgrip material would be favored for applications in which a less flexible, more-heat-resistant adhesive is required. An important point here is that thermal

TABLE 18. MOISTURE-BARRIER CHARACTERISTICS(a) OF VARIOUS SHEET/ADHESIVE COMBINATIONS

Sheet Material	Adhesive	Unexposed	WVTR, g/24 hr/m^2 at 23 C, 95% R.H. UV-500	UV-1000	TC-500	TC-1000
Acrylite	Acryloid B-7	(b)	3.31	4.95(b)	6.35(c)	9.31
Lexan	Acryloid B-7	6.01(c)	1.81	1.97	(b)	(b)
Sun-Lite	Acryloid B-7	3.90	4.63	4.44(b)	4.89	2.93
Acrylite	Scotch-Grip 4693	5.55	2.83	(d)	3.27	3.26
Lexan	Scotch-Grip 4693	1.34	2.62	1.63	3.36	3.38
Sun-Lite	Scotch-Grip 4693	3.53	3.76	4.09(b)	5.16	4.96
Acrylite	Silgrip SR 573	3.44	3.03	2.75	3.52	(b)
Lexan	Silgrip SR 573	1.41	1.82	1.66	3.64	4.41
Sun-Lite	Silgrip SR 573	3.76	5.53	3.96	6.06	5.25

(a) Measurements were performed in duplicate.

(b) These samples failed.

(c) One of two samples on test failed.

(d) Bubbles formed in the adhesive after lamination.

TABLE 19. "TEFLON" FEP FILM LAMINATE BOND EVALUATIONS

Adhesive	Lap Shear[a], 10^4 N/m^2					Predominant Failure Mode
	Unexposed	1000-Hour UV Exposure	1000-Hour Temperature Cycling	1000-Hour Thermal Aging		
				58 C	90 C	
RTV 118	5.4-6.1	6.3	5.9-6.4	6.2	6.3	Film elongation[b]
Silastic 732 RTV	5.5-6.2	5.3-6.5	4.6-6.5	6.1	6.3	ditto
Silgrip SR-573 (1.5% benzoyl peroxide)	6.1-6.2	6.3-6.4	6.2-6.4	6.0	6.2	"
Scotch-Weld 2216B/A	6.1-6.2	6.2-6.4	6.2-6.5	6.2	6.3	"
Cavalon 3100S (Activator 3300S)	3.3-6.1	6.2-6.3	6.2-6.3	6.2	6.1	"

(a) The calculations of bond strength are based on a bond area of 6.45 cm^2 (1 $in.^2$); 1 N/m^2 = 1.45×10^{-4} psi.

(b) "Film elongation" indicates that the specimen elongated but not in the bond area. The bond strength indicated, in such cases, is equal to or smaller than the actual bond strength.

cyclings of 1000 hours (250 cycles) produced no delaminations. This appears to be an inherent advantage of the use of the film (sheet) laminate encapsulation design with low-modulus (flexible) adhesives.

Bonding to Mylar Film. The five adhesives evaluated with 178-μm-thick Mylar all failed adhesively or cohesively. This was not unexpected in the unexposed samples since the data suggest a tensile strength in excess of 69.0×10^4 N/m^2 (100 psi) for the Mylar. However, it also was found that bond strengths generally were not markedly affected by the different types of environmental exposures (Table 20).

As in other studies, it was observed that the Cavalon 3100S with Activator 3303S discolors when exposed to UV or heat. With the Scotch-Grip 4693 and Silgrip SR-573 (1.5 percent benzoyl peroxide), bond strengths appear to improve after exposure to UV or thermal cycling. Thermal treatment improves bond strength, probably through further curing, as can be seen from the data for the thermally aged samples. An exception is the behavior of Scotch-Grip 4693 at 90 C. The three other adhesives seem to be completely unaffected by environmental exposures. Here again it should be noted that the low moduli of the adhesives used in bonding Mylar prevented any delamination during thermal cycling (–40 C to 90 C) after 1000 hours of exposure.

Bonding to Tuffak Film. Bond-test data obtained with Tuffak film (508-μm-thick) are presented in Table 21. This film has a yield strength of approximately 103 to 110×10^4 N/m^2 (150 to 160 psi). Two adhesives, the Scotch-Weld 2216 B/A and Structural Adhesive 3532 B/A, provided laminate bond strengths in excess of this yield strength; 3532 B/A is an unclear urethane and was the only adhesive from this class of materials that was available at the time of this work. It should provide a measure of the general effectiveness of this class of adhesives with Tuffak.

The adhesive next in order of effectiveness was the Silgrip SR-573 (1.5 percent benzoyl peroxide). Bond strengths with this material were somewhat lower than film yield strength, but were not adversely affected by UV or thermal cycling. To the contrary, as noted in other studies with this adhesive, some further curing occurred and bond strength increased. The improvement with curing was particularly noticeable with thermal controls, with bond strengths in the 62 to 76×10^4 N/m^2 (90 to 110 psi) range being obtained.

The two plastic adhesives (Scotch-Grip 4475 and Scotch-Grip 4693) were affected by one or more of the exposures. Scotch-Grip 4475 again was affected by the 90 C thermal cycling exposure and by thermal aging at 90 C. In both exposures, specimen delamination occurred. Bond strengths with Scotch-Grip 4693 were reduced markedly by UV exposure after as few as 500 hours of exposure. The bonds maintained strengths on thermal aging at 58 C. However, this adhesive subsystem is affected by higher temperatures; delamination occurred during aging at 90 C.

Both 4475 and 4693 are supplied with solvent, as are most "contact" adhesives. It is likely that the solvents in these adhesives caused film crazing; delamination may have resulted from built-in stresses produced by solvent effects. Note that here again the moderately low-modulus structural adhesives (2216 B/A and 3532 B/A) and the nonstructural Silgrip SR-573 did not delaminate during the thermal cycling study.

Bonding to Korad A. Bond-strength measurements were made for five adhesives with Korad A (152 μm thick). These data are listed in Table 22. With all but Silastic 732 RTV,

TABLE 20. MYLAR FILM LAMINATE BOND EVALUATIONS

	Lap Shear, 10^4 N/m^2(a)					
				1000-Hour Thermal Aging		
Adhesive	Unexposed	1000-Hour UV Exposure	1000-Hour Temperature Cycling	58 C	90 C	Predominant Failure Mode
Scotch-Grip 4693	47-60	65-70	69-71	76	59	Cohesive failure
RTV-118	25-45	47-60	24-58	51	63	Adhesive/ cohesive failure
Scotch-Weld 3520 B/a	46-48	52-55	45-50	58	56	Adhesive failure
Cavalon 3100S (Activator 3303S)	48-68	41-67	57-68	48	54	Adhesive failure
Silgrip SR-573 (1.5% benzoyl peroxide)	37-46	48-66	70-76	68	70	Cohesive failure

(a) 1 N/m^2 = 1.45 x 10^{-4} psi.

TABLE 21. TUFFAK FILM LAMINATE BOND EVALUATIONS

	Lap-Shear, 10^4 N/m^2(a)					
				1000-Hour Thermal Aging		
Adhesive	Unexposed	1000-Hour UV Exposure	1000-Hour Temperature Cycling	58 C	90 C	Predominant Failure mode
Scotch-Grip 4475	105-113	105-109	delamination	112	delamination	Film elongation(b)
Scotch-Grip 4693	47-83	0-8.6	37-83	56	delamination	Cohesive failure
Structural Adhesive 3532 B/A	105-119	97-112	110-113	111	114	Film elongation
Silgrip SR-573, 1.5% benzoyl peroxide	13-37	19-39	18-51	73	62	Cohesive failure
Scotch-Weld 2216 B/A	104-113	113	110-117	112	124	Film elongation

(a) 1 N/m^2 = 1.45×10^{-4} psi.

(b) "Film elongation" indicates that the specimen elongated but not in the bond area. The bond strength indicated, in such cases, is equal to or smaller than the actual bond strength.

TABLE 22. KORAD A FILM LAMINATE BOND EVALUATIONS

	Lap-Shear, 10^4 N/m^2 (a)					
			1000-Hour	1000-Hour Thermal Aging		Predominant
Adhesive	Unexposed	1000-Hour UV Exposure	Temperature Cycling	58 C	90 C	Failure Mode
Silastic 732 RTV	10-13	12-14	10-11	13	11	Adhesive failure
Silgrip SR-573, SRC-30	16-18	19	18	18	18	Film elongation(b)
Scotch-Weld 2216 B/A	16-18	17-19	17-18	18	17	Film elongation
Scotch-Grip 4693	17-18	15-17	18	18	17	Film elongation
Scotch-Grip 4475	16-18	11-14	18	18	18	Film elongation

(a) 1 N/m^2 = 1.45 x 10^{-4} psi.

(b) "Film elongation" indicates that the specimen elongated but not in the bond area. The bond strength indicated, in such cases, is equal to or smaller than the actual bond strength.

failure occurred by film elongation, indicating that the adhesive is as strong or stronger than the yield value of the film, which is approximately 17 to 19 x 10^4 N/m^2 (25 to 27 psi).

Exposure to UV and thermal cycling had no effect on Silastic 743 RTV, Silgrip SR-573, or Scotch-Weld 2216 B/A. Bond strengths with Scotch-Grip 4693 and Scotch-Grip 4475 were not affected by thermal cycling, but some slight deterioration upon UV exposure was observed after 1000 hours. Interestingly, no delaminations occurred with either during 90 C thermal aging. It appears that except for 732 RTV all adhesives tested are satisfactory for bonding Korad A.

Bonding to Tedlar Film. The yield strength of 102-μm-thick Tedlar film appears to be approximately 15 x 10^4 N/m^2 (22 psi). In the study of the bonding of Tedlar with five selected adhesives, film elongation was the predominant failure mode, both before and after environmental exposures (Table 23). Only unexposed specimens containing Cavalon 3100S (5 percent benzoyl peroxide) failed adhesively or cohesively (that is, at a strength much below 15 x 10^4 N/m^2). Even with this material, however, further curing appeared to occur during exposures and bond strengths improved. Some "wetting-out" problems were observed on the unexposed Silgrip SR-573 with SRC-30. Scotch-Weld 2216 B/A and Silastic 732 RTV appear to be the best overall performers with Tedlar.

Bonding to Flexigard Film. Four of the five adhesives selected for evaluations on Flexigard film (127-μm thick) were strong enough to cause film elongation for the majority of the specimens evaluated (Table 24). Film yield strength appears to be 23 to 26 x 10^4 N/m^2 (33 to 37 psi). Film bond strengths with Silastic 732 RTV were somewhat affected by thermal aging and thermal cycling, and adhesive-type failures predominated. Cavalon 3100S (1.5 percent benzoyl peroxide) again failed either cohesively or adhesively before exposure and improved with exposures, apparently as further curing took place. The other three adhesives (Scotch-Weld 2216 B/A, Scotch-Grip 4693, and Silgrip SR-573 with SRC-30) were unaffected by the several types of exposure.

A shortcoming with Flexigard appears to be the care required in applying the various adhesives to optimize performance. With the exception of Scotch-Weld 2216 B/A, an adhesive recommended by the manufacturer of Flexigard, film/adhesive composites generally are difficult to prepare with good optical clarity. Work to define application techniques will be necessary with a majority of the adhesives candidates.

Evaluations of Polymer Encapsulated Cells

The ultimate judgment of the performance of encapsulation systems hinges upon how well the electrical characteristics of the encapsulated cell are maintained over time. Accordingly, individual cells were encapsulated with selected materials and exposed to an environment characterized by 100 percent relative humidity at 38 C. All the cell electrical characteristics listed in a previous section of this report were measured periodically, roughly in 100-hour increments. In the results presented below, the characteristics reported are short-circuit current (I_{sc}), maximum power level (P_{max}), and series resistance (R_s). These characteristics relate directly to the utility of the encapsulants. Because of the differences in the characteristics of the unencapsulated cells, the changes in characteristics are emphasized. Original values, prior to exposure but following encapsulation, are also listed in the results.

TABLE 23. TEDLAR FILM LAMINATE BOND EVALUATIONS

Adhesive	Lap-Shear, 10^4 N/m^2(a) Unexposed	1000-Hour UV Exposure	1000-Hour Temperature Cycling	1000-Hour Thermal Aging 58 C	1000-Hour Thermal Aging 90 C	Predominant Failure Mode
Silastic 732 RTV	13-14	14	14-15	14	15	Film elong.(b)
Scotch-Weld 2216 B/A	13-14	14-15	14-15	15	15	Film elongtion
Silgrip SR-573, SRC-30	11-14	14	14-15	14	15	Film elongation
Cavalon 3100S (Activator 3303S)	13-14	14	15	14	15	Film elongation
Cavalon 3100S, 5% benzoyl peroxide	5-10	10-14	14	14	14	Film elongation

(a) 1 N/m^2 = 1.45 x 10^{-4} psi.

(b) "Film elongation" indicates that the specimen elongated but not in the bond area. The bond strength indicated, in such cases, is equal to or smaller than the actual bond strength.

TABLE 24. FLEXIGARD FILM LAMINATE BOND EVALUATIONS

Adhesive	Lap Shear, 10^4 N/m^2(a)					Predominant Failure Mode
	Unexposed	1000-Hour UV Exposure	1000-Hour Temperature Cycling	1000-Hour Thermal Aging		
				58 C	90 C	
Scotch-Weld 2216B/A	23-27	25-28	23-25	34	25	Film elongation(b)
Cavalon 3100S (1.5% benzoyl peroxide)	10-11	24-31	24-25	24	26	Film elongation(b)
Scotch-Grip 4693	20-23	25-27	23-24	25	26	Film elongation
Silgrip SR-573, SRC-30	24	24-26	23	24	24	Film elongation
Silastic 732 RTV	18-23	15-21	14-19	16	16	Adhesive failure

(a) 1 N/m^2 = 1.45 x 10^{-4} psi.

(b) "Film elongation" indicates that the specimen elongated but not in the bond area. The bond strength indicated, in such cases, is equal to or smaller than the actual bond strength.

Some care must be exercised in differentiating the initial screening results for various encapsulants. In the level of effort of Phase I of this program, only single specimens could be made and tested. Further replication and exposure were carried out in Phase II and are reported subsequently. In many of the results that follow, the changes in the values of electrical characteristics following a given exposure time (most often between 450 and 500 hours) are given. As noted, the values were measured periodically during this period. Although they were usually not extreme, changes occurred (both increases and decreases) during the total exposure period. That is, the changes were not monotonic in time. Thus, the data should be taken as an indication of trends rather than absolute values. Moreover, the data do not represent the amount of absorption of light by the encapsulant, as represented in the short-circuit current. Light transmittance of materials was treated previously in this report.

Evaluations of Adhesives Alone as Encapsulants. Adhesives are not likely to be used as the sole encapsulant. However, some adhesive exposure to the outside environment, such as a bond edge, is likely. One of the chief environmental parameters which would be expected to degrade many adhesives is water vapor. So as to help differentiate adhesives in a short period of time, cells encapsulated with selected adhesives alone were exposed to a high-humidity environment. Table 25 identifies the adhesives, their formulation, and the changes in I_{sc}, P_{max}, and R_s. The order of the listing is based on increasing percentage of reduction in P_{max}. Of course, an increase in R_s indicates degradation, a result most likely originating from an interaction of water vapor, or the adhesive, with the collecting grids.

On the basis of changes in P_{max}, the epoxy, Scotch-Weld 2216 B/A, gave the best performance, followed closely by the polyurethane system, Chemlok 7000/7203. Note that for both Chemlok systems, the coating weight was small; better performance might be expected with a heavier coating. Note also that the laminating urethane, B 2397-10, performed rather poorly in this test with a thin coating. Its viscosity is low. The urethane adhesives are of interest, in part, because they are among the best adhesives for bonding polycarbonate film or sheet.

Except for the uncoated one, most cells exhibited a rather small decrease in short-circuit current. This result might be expected since the adhesives are stable in the presence of water vapor, although some are permeable to this vapor. The series resistance increased sizably for all cells. The Chemlok 7000/7203 system gave the best performance. Such increases as found in this characteristic (R_s) are obviously serious, suggesting that the concentration of water vapor at the collecting grid should be kept low. One cannot rule out the possibility, however, that mechanical stress introduced into the grid system as a result of the polymerization of the adhesive leads to degradation of the bond between the grid and the silicon cell.

Evaluations of Conformal Coating Encapsulants. Five classes of resins were evaluated in the coatings selected for high-humidity exposure: polyvinyl butyral, polyacrylate, epoxy, polyurethane, and silicone (both moisture-cured and thermally activated types). Electrical data for the nine conformal coatings selected for this evaluation together with information on coating weights, dilution and mixing ratios, and method of drying or curing are given in Table 26. Again, the listing reflects an increasing percentage reduction in P_{max}, except for GR-70105-1.

Polyvinyl Butyral. This material was examined both as a solution in an organic solvent and as a dispersive grade in an aqueous medium. The latter did not completely wet the cell surface, while the organic solvents were prone to entrapment and caused some blistering during drying.

TABLE 25. SUMMARY EVALUATIONS OF ELECTRICAL CHARACTERISTICS OF SOLAR CELLS COATED WITH SELECTED ADHESIVE/POTTANT MATERIALS BEFORE AND AFTER EXPOSURE TO 100 PERCENT R.H. AT 38 C

Material	Description	Dilution and/or Mix Ratio	Coating Weight per Unit Area, mg/cm^2	Electrical Property	Property Value Before Exposure	Change in Property Value After 440-550 Hours of Exposure, percent
Scotch-Weld 2216 B/A$^{(a)}$	Epoxy	(1/1) A/B; (2/1) 2216/MEK	8.4	I_{sc} (mA) P_{max} (mW) R_x (mΩ)	580 194 146	+ 0.2 - 3.6 + 33.6
Chemlok 7000/Chemlok 7203$^{(b)}$	Polyurethane	(20/1) 7000/7203; (1/1) resin/MEK	5.8	I_{sc} (mA) P_{max} (mW) R_x (mΩ)	575 186 186	- 2.1 (650-700)$^{(g)}$ - 4.3 (650-700)$^{(g)}$ - 9.1 (650-700)$^{(g)}$
Silgrip SR-573$^{(c)}$	Silicone resin	(5/3) SR-573/toulene	18.7	I_{sc} (mA) P_{max} (mW) R_s (mΩ)	580 198 210	- 1.0 - 8.1 + 66.7
Scotch-Grip 4475$^{(c)}$	Plastic adhesive	none	14.0	I_{sc} (mA) P_{max} (mW) R_s (mΩ)	564 196 143	- 1.1 - 10.2 - 42.0
Scotch-Grip 4693$^{(c)}$	Plastic adhesive	none	7.6	I_{sc} (mA) P_{max} (mW) R_s (mΩ)	559 195 133	+ 0.7 - 11.8 + 42.9
Q3-6527 A/B (DC)$^{(d)}$	Silicone gel	(1/1) A/B	10.0	I_{sc} (mA) P_{max} (mW) R_s (mΩ)	598 195 172	- 2.0 - 13.3 + 47.1
Acryloid B-7$^{(c)}$	Acrylic (TP)	none	9.4	I_{sc} (mA) P_{max} (mW) R_s (mΩ)	578 215 182	- 1.4 - 13.5 + 28.6
Chemlok 7002/Chemlok 7203$^{(b)}$	Polyurethane	(20/1) 7002/7203 (1/1) resin/MEK	4.2	I_{sc} (mA) P_{max} (mW) R_s (mΩ)	568 177 184	- 2.8 (650-700) - 17.5 (650-700) + 26.1 (650-700)
RTV 118$^{(e)}$	Silicone	none	40.9	I_{sc} (mA) P_{max} (mW) R_s (mΩ)	594 208 217	- 2.2 - 28.9 + 74.2
B2397-10 (Hughson)$^{(f)}$	Laminating urethane	none	4.7	I_{sc} (mA) P_{max} (mW) R_s (mΩ)	532 185 207	- 1.9 (600-650)$^{(g)}$ - 40.5 (600-650)$^{(g)}$ + 125.6 (600-650)$^{(g)}$
Control	Uncoated cell			I_{sc} (mA) P_{max} (mW) R_x (mΩ)	603 178 183	- 15.4 - 55.1 + 62.8

(a) Ambient-temperature cured for 3 days.
(b) Moisture cured for 3 days at 23 C, 50 percent R.H.
(c) Air dried for 3 days.
(d) Ambient-temperature cured for 3 days, then baked in forced-air oven at 135 C for 30 minutes.
(e) Moisture cured for 1 week at 23 C, 50 percent R.H.
(f) Air-dried for 3 days, then baked in forced-air oven at 121 C for 10 minutes.
(g) Cells exposed in the range of hours listed.

TABLE 26. SUMMARY EVALUATIONS OF ELECTRICAL CHARACTERISTICS OF SOLAR CELLS CONFORMALLY COATED WITH SELECTED COATING MATERIALS BEFORE AND AFTER EXPOSURE TO 100 PERCENT R.H. AT 38 C

Material	Description	Dilution and/or Mix Ratio	Coating Weight per Unit Area, mg/cm^2	Electrical Property	Property Value Before Exposure	Change in Property Value After 450-550 Hours of Exposure, percent
Eccocoat AC-8(a)	Polyacrylate	(10/3) AC-8/toluene	14.4	I_{sc} (mA)	580	0.0
				P_{max} (mW)	214	− 5.6
				R_s (mΩ)	133	+ 12.8
DC 3140 RTV(b) plus 1204 Primer(c)	Silicone		6.5	I_{sc} (mA)	590	− 2.5
				P_{max} (mW)	204	− 7.8
				R_s (mΩ)	298	− 45.0
Butvar B-98(d)	Polyvinyl butyral	25% solution in ethanol	13.8	I_{sc} (mA)	570	− 10.2
				P_{max} (mW)	200	− 16.5
				R_s (mΩ)	187	+ 33.7
Eccocoat RTU(e)	Polyurethane	(1/1) A/B	9.8	I_{sc} (mA)	568	0.0
				P_{max} (mW)	203	− 16.8
				R_s (mΩ)	188	+ 108.0
Butvar B-79(f)	Polyvinyl butyral	15% solution in ethanol	1.9	I_{sc} (mA)	565	− 3.9
				P_{max} (mW)	197	− 19.8
				R_s (mΩ)	159	+ 102.5
GR-70105-2(g)	Modified silicone resin	25% solution in alcohol	3.8	I_{sc} (mA)	577	− 3.3
				P_{max} (mW)	180	− 20.0
				R_s (mΩ)	203	+ 53.7
Eccocoat VE(h)	Epoxy	(1/1) A/B; (3/2) VE/Solvent(i)	15.7	I_{sc} (mA)	580	− 2.1
				P_{max} (mW)	201	− 30.9
				R_s (mΩ)	191	+ 86.9
Glass Resin 650(j)	Silicone resin	50% solution in ethanol	8.6	I_{sc} (mA)	512	− 11.7 (601-650)
				P_{max} (mW)	168	− 39.9 (601-650)
				R_s (mΩ)	43	+ 1011.6 (601-650)
GR-70105-1(k)	Silicone resin	25% solution in ethanol	7.0	I_{sc} (mA)	451	+ 1.6 (1-50)(1)
				P_{max} (mW)	153	0.0 (1-50)(1)
				R_s (mΩ	169	+ 21.9 (1-50)(1)
Control	Uncoated cell			I_{sc} (mA)	601	− 15.4
				P_{max} (mW)	178	− 55.1
				R_s (mΩ)	183	+ 62.8

(a) Air dred only (4 days).
(b) Moisture cured 1 week at 23 C, 50 percent R.H.
(c) Primer 1204 air dried for 1 hour before 3140 RTV was applied over it.
(d) Air dried only (3 days).
(e) Moisture cured for 3 days at 23 C, 50 percent R.H.
(f) Air dried 16 hours, then baked in forced-air oven 10 minutes at 135 C.
(g) Air dried for 3 days, then cured 24 hours at 135 C.
(h) Air dried and ambient temperature cured for 3 days.
(i) Solvent ratio was 1/1 toluene/MEK.
(j) Air dried for 3 days, then cured 24 hours at 135 C. Coating crystallized but did not flake off.
(k) Air dried for 3 days, then cured 24 hours at 135 C.
(1) Coating crystallized and started flaking off solar cell.

Polyvinyl butyral gave a clear coating before exposure to high humidity, but the coating became somewhat milky (opaque to the eye) after exposure.

Butvar B-79 exhibited more rapid degradation of P_{max} and R_s than did Butvar B-98, probably due mainly to reduced coating thickness. The B-98 tended to become milky more rapidly, possibly due to the fact it was air dried, whereas the other coating was baked for 10 minutes at 135 C following air drying.

Eccocoat AC-8. Coatings of Eccocoat AC-8, a polyacrylate, were applied and allowed to air dry without subsequent baking. In preliminary studies, baking consistently led to blistering. Dilution of the as-supplied material with ketone exaggerated the blistering. The method used with best results was dilution with toluene followed by air drying. Degradation of electrical properties between 1 and 50 hours and 450 and 550 hours was less than that for most other coatings listed. The coating was affected by high humidity, however; it became somewhat milky after only limited exposure.

Eccocoat VE. Equal portions of resin and hardener were used in formulating the coating and the mixture was diluted with a 1/1 toluene/MEK mixture. This formulation was applied to the cell and allowed to cure at room temperature (23 C, 50 percent R.H.) for 3 days. The epoxy coating did not wet the solar cell surface well, and the cured coating performed rather poorly, although high humidity did not affect the coating appearance.

Eccocoat RTU. This coating was prepared by mixing equal portions of resin and curing agent. The urethane coating remained clear throughout most of the test period, becoming spotty in appearance after only about 3 weeks of exposure. This coating gave slightly better protection from high humidity than the epoxy, but would not be considered a leading candidate.

Silicone Coatings. Moisture-cure (3140 RTV) and thermal-curing types (Glass Resin 650 and a modification) of silicones were studied. The glass resins were supplied as 25 percent solution in alcohol (GR-70105-1 and GR-70105-2). A third was prepared at Battelle-Columbus as a 50 percent solution in ethanol.

Neither the unmodified Glass Resin 650 nor GR-70501-1, when applied at 7 to 9 mg/cm^2, performed well. The latter actually crystallized and tended to flake off the cell. The modified Glass Resin 650 coating (GR-70105-2) was applied at 4 mg/cm^2 and did not crystallize. Even so, electrical performance was poor. The most promising of the silicone coatings was 3140 RTV. The protection imparted to the cell by this material was equivalent to that provided by the acrylic, although it too became somewhat milky during 3 weeks of exposure to high humidity.

Evaluations of Cells Encapsulated With Film or Sheet Laminates. The types of encapsulation evaluated here are basically those identified in Figures 4 and 5, with a polymer film or foil being used as the bottom member ("substrate") of the laminate. The specific components of the eight laminates are identified in Table 27.

Laminated systems employing the Scotch-Weld 2216 B/A, flexible epoxy adhesive were prepared by placing the cell between previously coated cover and substrate materials and gently

TABLE 27. CONSTRUCTION OF FILM AND SHEET LAMINATES USED IN HIGH-HUMIDITY CELL PERFORMANCE STUDIES

Identification	Top Cover (Thickness, μm)	Adhesive	Substrate (Thickness, μm)
Acrylite	Acrylite (3175)	Scotch-Weld 2216B/A	Aluminum Foil (102)
Flexigard	Flexigard (127)	Silgrip SR-573	Flexigard (127)
Mylar	Mylar (178)	Silgrip SR-573	Mylar (178)
Sun-Lite - 1	Sun-Lite (635)	Scotch-Weld 2216B/A	Aluminum Foil (102)
Sun-Lite - 2	Sun-Lite (635)	Silgrip SR-573	Aluminum Foil (102)
Tedlar	Tedlar (102)	Ditto	Tedlar (102)
"Teflon" FEP-1	"Teflon" FEP (127)	"	"Teflon" FEP (127)
"Teflon" FEP-2	"Teflon" FEP (127)	"	Alure CX(a) (89)

(a) A composite of a metallized polyester (0.5 mil) and a coextruded high-density polyethylene (3.0 mil) manufactured by St. Regis.

forcing entrapped air to the edges. The lamination was cured for 2 days at room temperature under slight pressure and then was given a final cure of 2 hours at 70 C. The thickness of the adhesive around the cell was 381 μm (15 mils). The encapsulated cells were free of air bubbles.

Laminates containing Silgrip SR-573 were prepared at 130 C. The cover and backing materials were coated with Silgrip SR-573 adhesive and allowed to dry at room temperature. The cell was placed between the coated cover and backing materials and laminated using 152 μm (6 mil) brass templates to prevent cracking. The thickness of the adhesive around the cell was approximately 152 μm (6 mil) and free of air bubbles.

As with the adhesives and conformal coatings, cell performance during exposure to high-humidity environments was monitored periodically. Table 28 identifies the change in properties of I_{sc}, P_{max}, and R_s after a specified number of hours. As before, the listing of laminates is made in the order of increasing reduction of P_{max}. Expectedly, the degradation in P_{max} and the other parameters is generally less than that with the adhesives and coatings alone. However, degradation of P_{max} is still substantial when viewed in light of a 20-year life. Significantly, the series resistance decreased for three laminates. Note that the laminate using the acrylite sheet – number one in the listing – exhibited a small value of R_s; moreover, the value decreased after 648 hours. The "Teflon" FEP/"Teflon" FEP laminate also exhibited a decrease in R_s, and, in addition, exhibited a relatively small reduction in P_{max}. But as noted previously, one should be careful in drawing general conclusion without sufficient replication of specimens. (See results of Phase II.)

Results for Encapsulation Systems Employing a Glass Component

The results of the evaluations of material systems employing glass as the top cover, and in some cases also as the substrate, are described in this section of the report. Results of cells encapsulated with a glass component, a summary of data on adhesive properties, and an evaluation of adhesives and sealants appropriate for glass systems are treated.

In this investigation, the cells were encapsulated and their electrical performance measured after cell cleaning, after encapsulation, and after exposure to thermal cycling and UV radiation. (Procedures were identified in an earlier section of this report.)

Effects of Encapsulation Alone on Cell Performance

Cell electrical parameters were measured after cleaning and after encapsulation. The results are given in Table 29. Refer to Figure 6 for identification of the types of laminates.

The effects in percentage change of encapsulation alone (before exposure) on I_{sc}, P_{max}, and R_s are shown in Table 30. Several points can be seen from these data. The use of the borosilicate cover led to an increase in I_{sc} of about 5 percent for all adhesives used. P_{max} increased in the range 6 to 16 percent. R_s decreased significantly for all these cases. In somewhat of a contrast, the use of soda-lime covers led to either no change or to a small decrease in I_{sc}. Small increases in P_{max} occurred except for the soda-lime/Sylgard 184 combination. Both decreases and increases were found in R_s.

TABLE 28. SUMMARY EVALUATIONS OF ELECTRICAL CHARACTERISTICS OF SOLAR CELLS ENCAPSULATED (LAMINATES) WITH FILM AND SHEET MATERIALS BEFORE AND AFTER EXPOSURE TO 100 PERCENT R.H. AT 38 C

Laminate Materials	Electrical Property	Property Value Before Exposure	Change in Property Value, percent	Exposure Time, hours
Acrylite Sheet/Scotch-Weld 2216 B/A/ Aluminum Foil	I_{sc} (mA)	589	- 2.9	648
	P_{max} (mW)	227	- 4.0	648
	R_s (mΩ)	82	- 7.3	648
"Teflon" FEP Film/Silgrip SR-573/ "Teflon" FEP Film	I_{sc} (mA)	608	- 4.3	576
	P_{max} (mW)	203	- 4.4	576
	R_s (mΩ)	161	- 2.5	576
Flexigard Film/Silgrip SR-573/ Flexigard Film	I_{sc} (mA)	578	- 0.9	480
	P_{max} (mW)	185	- 6.5	480
	R_s (mΩ)	177	+ 36.7	480
Sun-Lite Sheet/Scotch-Weld 2216 B/A/ Aluminum Foil	I_{sc} (mA)	578	- 6.2	648
	P_{max} (mW)	213	- 9.4	648
	R_s (mΩ)	161	+ 24.8	648
Tedlar Film/Silgrip SR 573/ Tedlar Film	I_{sc} (mA)	590	- 2.5	480
	P_{max} (mW)	190	- 9.5	480
	R_s (mΩ)	206	+ 4.4	480
"Teflon" FEP Film/Silgrip SR-573/ Alure CX	I_{sc} (mA)	582	- 0.3	480
	P_{max} (mW)	191	- 12.0	480
	R_s (mΩ)	103	+ 89.3	480
Sun-Lite Sheet/Silgrip SR-573/ Aluminum Foil	I_{sc} (mA)	591	- 4.4	576
	P_{max} (mW)	215	- 13.5	576
	R_s (mΩ)	113	+ 42.5	576
Dyed Mylar Film/Silgrip SR-573/ Dyed Mylar Film	I_{sc} (mA)	555	- 7.6	480
	P_{max} (mW)	198	- 18.7	480
	R_s (mΩ)	132	- 13.6	480

TABLE 29. EFFECTS OF GLASS ENCAPSULATION ALONE ON ELECTRICAL CHARACTERISTICS OF CELLS[(a)]

Test Laminate Description					Cell Performance After Indicated Stage of Processing: Cleaned Cell									Cell Performance After Indicated Stage of Processing: Encapsulated Cell Before Screening Tests								
Identification	Glass-to-Cell Adhesive[(b)]	Primer Used on Cell and Glass	Glass Type	Laminate Type[(d)]	V_{oc}	I_{sc}	V_{mp}	I_{mp}	P_m	η	FF	R_s	R_{sh}	V_{oc}	I_{sc}	V_{mp}	I_{mp}	P_m	η	FF	R_s	R_{sh}
33123-32-1(055)	Sylgard 184	Dow Q36-060	Soda-lime float	A	552	571	420	493	207	11.4	.657	97	125	558	558	430	465	200	11.1	.642	141	100
33123-32-4(022)	Ditto	Ditto	Ditto	B	572	585	445	500	223	12.3	.665	191	680	573	565	445	485	216	11.9	.667	150	495
33123-32-3(071)	"	"	"	C	541	568	415	466	193	10.7	.629	178	140	553	562	415	470	195	10.9	.628	117	125
33068-21-2(024)	"	"	7740 Borosilicate	A	529	581	405	495	200	11.1	.652	156	255	566	602	435	520	226	12.5	.664	67	230
33068-21-1(054)	"	"	Ditto	A	555	591	425	508	216	11.9	.658	137	295	570	621	445	518	231	12.7	.651	125	260
33123-32-5(041)	"	"	"	A	519	557	395	465	184	10.2	.635	204	670	566	601	445	498	222	12.2	.652	108	380
33123-32-6(067)	"	"	"	C	550	580	425	490	208	11.5	.653	194	890	558	610	425	520	221	12.2	.649	101	610
33123-14-1(032)	Dow 3140	Dow 1204	Soda-lime float	A	533	558	415	466	193	10.7	.650	167	620	556	563	425	484	206	11.4	.657	141	525
32123-14-2(036)	Ditto	Ditto	Ditto	A	551	608	405	489	198	10.9	.591	249	445	560	587	410	467	192	10.6	.582	207	180
33123-14-3(052)	"	"	"	B	534	572	400	472	189	10.4	.618	245	385	542	550	410	447	183	10.1	.610	106	200
33123-14-5(045)	"	"	"	B	539	562	400	479	192	10.6	.633	187	310	560	530	435	438	191	10.5	.642	144	250
33123-14-4(043)	"	"	"	C	533	578	415	497	206	11.4	.670	158	625	558	568	435	492	214	11.8	.675	128	610
33123-14-6(072)	"	"	7740 Borosilicate	A	549	580	430	480	206	11.4	.648	153	550	568	606	435	517	225	12.4	.653	90	480
33123-14-8(073)	"	"	Ditto	B	530	570	385	460	177	9.8	.506	170	180	552	571	400	472	189	10.4	.599	125	130
33123-14-9(062)	"	"	"	C	554	569	435	499	217	12.0	.689	160	410	548	601	435	513	224	12.4	.680	98	395
33068-17-4(064)	Dow Q3-6527	None	Soda-lime float	A	544	571	420	499	210	11.6	.675	112	600	550	571	435	488	212	11.7	.676	120	625
33068-17-1(019)	Ditto	None	7740 Borosilicate	A	544	518	415	483	200	11.1	.637	201	305	575	619	440	525	231	12.8	.649	153	470
33068-26(129)	PVB[(c)]	None	Soda-lime float	A	597	580	415	510	212	11.7	.667	177	260	565	561	435	497	216	12.0	.682	116	285
33068-30(116)	Ditto	Ditto	Ditto	A	539	602	395	490	194	10.7	.597	201	710	560	562	415	464	193	10.6	.612	143	720
33068-27(130)	"	"	"	A	540	570	420	480	202	11.1	.655	187	460	570	536	450	454	204	11.3	.669	157	440

(a) Cell measurements: V_{OC} = open-circuit voltage, mv; I_{SC} = short-circuit current, ma; V_{MP} = max voltage, mv; I_{MP} = max current, ma; P_M = max power, mw; η = efficiency, percent; FF = fill factor; R_S = series resistance of cell, mΩ; R_{SH} = shunt resistance, ohms.

(b) Sylgard 184, 2-part silicone rubber; Dow 3140, noncorrosive RTV silicone; Dow Q3-6527, dielectric silicone gel.

(c) Polyvinyl butyral, ∿ 760 μm (30 mils) between the cell and cover glass and between cell and back glass.

(d) For schematic description of laminate types, see Figure 6.

TABLE 30. AVERAGE CHANGES IN SELECTED CELL ELECTRICAL CHARACTERISTICS RESULTING FROM ENCAPSULATION ALONE

Test Laminate Constitutes		Change in Property Value, percent		
Glass Cover	Cell-to-Glass Adhesives	I_{sc}	P_m	R_s
Soda-Lime	Sylgard 184	-2	-1	+11
7740-Borosilicate	ditto	+5	+12	-40
Soda-Lime	Dow 3140	-1	+3	-17
7740-Borosilicate	ditto	+6	+6	-40
Soda-Lime	Q3-6527 Gel	0	+1	+7
7740-Borosilicate	ditto	+7	+16	-24
Soda-Lime	PVB	-5	+1	-26

Causes for these changes are likely to stem from two sources. The borosilicate glass exhibits less absorption in the earth solar spectrum than the soda-lime glass. This fact leads to higher I_{sc}. In addition, the optical coupling with borosilicate glass could be better matched to the laminate. The reason for the variation in R_s is not clear. Significantly, R_s decreased except in two cases. It is to be noted that considerable scatter occurred in the R_s values from cell to cell.

Effects of Thermal Cycling and UV on Electrical Performance of Glass-Encapsulated Cells

Test laminates were measured for electrical performance after sequential exposures to thermal cycling and to UV radiation. Because the laminate edges were not hermetically sealed, the encapsulated test cells were also accessible to moisture. For cells encapsulated in Type A laminates (see Figure 6), the moisture would have had to migrate through the adhesive to reach the cell. For Type B test laminates, the peripheral area of the cells was not coated with adhesive, and this area was directly accessible to moisture in the test atmosphere. Similarly, the uncoated back surface of cells in Type C laminates was directly accessible to the moisture in the test atmosphere. Thus, the screening tests subjected laminate test cells to thermal stress, UV radiation, and moisture.

The accumulated changes in selected electrical characteristics after exposures of these specimens to UV and thermal cycling (plus moisture) are summarized in Table 31. Note that V_{oc} and I_{sc} changed only a moderate amount, while P_{max} for some specimens decreased by as much as 30 percent. Thus, the major cause of the decrease in P_{max} must be assigned to increases in R_s. Since the glasses are not expected to degrade significantly in these exposures, the degradation is likely due to degradation of the adhesives. Recall that no edge sealing was employed. Optical absorption changes in the adhesives likely had some effects but not major ones. Again, changes in I_{sc} were not large. One must tentatively conclude, therefore, that effects of water vapor on the bonds between the metallization and cells were major contributors to decreases in P_{max}.

Further results with glass and polymer encapsulants are presented in the next report section. Selected encapsulants, chosen based on the Phase I results, were subjected to longer exposures, and specimens were replicated.

TABLE 31. SUMMARY OF ACCUMULATED CHANGES IN ELECTRICAL CHARACTERISTICS OF GLASS-ENCAPSULATED CELLS WITH AGING AND EXPOSURE TO UV RADIATION AND THERMAL CYCLING

	Type of Laminate(a)		Accumulated Test Exposures, hr		Original Values and Accumulated Changes in Electrical Characteristics									
					V_{oc} (d)		I_{sc}		P_{max}		R_{sh}		R_s	
Laminate No.	Glass (Cover and Back)	Adhesive (Cell-to-Glass)	UV(b)	Thermal(c) Cycle	I(d)	Δ, %	I	Δ, %	I	Δ, %	I	Δ, %	I	Δ, %
33123-32-1(055)	Float	Sylgard 184	1600	504	0.558	-1	0.558	-2	0.200	-15	100	+2	0.141	+55
33123-32-5(041)	7740	Sylgard 184	1410	504	0.566	-2	0.601	-2	0.222	-13	380	-47	0.108	+77
33068-21-2(024)	7740	Sylgard 184	1600	504	0.566	0	0.602	-9	0.226	-22	230	+6	0.068	+235
33123-14-1(032)	Float	Dow 3140	1600	504	0.556	-1	0.563	-3	0.206	-30	525	-53	0.141	+184
33123-14-6(072)	7740	Dow 3140	1600	504	0.568	0	0.606	-2	0.225	-19	480	-58	0.090	+217
33068-17-4(064)	Float	Q3 6527	1600	504	0.550	+1	0.571	-4	0.212	-15	625	-35	0.147	+68
33068-26(129)	Float	PVB	1410	463	0.565	+1	0.561	-2	0.216	-2	285	+60	0.116	+53
33068-30(116)	Float	PVB	1055	374	0.560	-1	0.562	+1	0.193	-25	720	+102	0.143	+51
33068-27(130)	Float	PVB	1240	412	0.570	0	0.536	+2	0.204	0	440	+96	0.187	-5

(a) The edges of these double glass laminates are not sealed; thus the cells (encased in adhesive) are exposed to the test atmosphere. The total age of the laminates was approximately 13 months.

(b) Laminates were exposed to the same xenon lamp UV test environment as polymer-encapsulated cells (average of 50 C and ambient humidity).

(c) Thermal cycling from -40 to +90 C on a 4-hour cycle.

(d) "I" stands for initial value (after encapsulation); V_{oc} in volts; I_{sc} in amperes; P_{max} in watts; R_{sh} and R_s in ohms.

PHASE II. RESULTS AND DISCUSSION OF EVALUATIONS OF SELECTED ENCAPSULATION MATERIALS AND ENCAPSULATED CELLS WITH REPLICATION

The first phase of this study consisted of a preliminary evaluation of a large number of candidate encapsulation materials and structures identified in an earlier review of encapsulation experience and materials properties.(3,7) On the basis of this initial screening, the more promising candidate materials were then selected for more detailed evaluation, employing replication (usually 5) to develop data with reasonable statistical validity. The results of this second phase are summarized in this section.

More specifically, this section contains the results of the following investigations:

- Normal light transmittance of polymer sheet/film materials alone and with selected adhesives applied
- Changes in the electrical characteristics of individual solar cells after exposure to artificial environments when encapsulated with the following classes of materials:
  - conformal polymer coatings
  - polymer sheet/film materials
  - glasses.

Normal Light Transmittance of Polymer Sheet/Film Materials

A critical evaluation parameter for cover materials for cells is, of course, the transmittance of the cover material itself and the combination of the material and the adhesive used to attach the cover to the cell. The normal transmittance was measured for selected sheet/films with and without adhesives in the wavelength range 3000 to 12,000 A. Such data were taken before and after exposure to 2515 hours of ultraviolet radiation (approximately 1 sun). Table 32 identifies the selected films and adhesives, and presents the measured results. See Tables 2 and 3 for further identification of the materials employed. Note that in Table 32, the wavelength range of 3000 to 12,000 A is covered only for the unexposed samples. Equipment troubles prevented obtaining comparable postexposure data in the 7000 to 12,000 A range. Note also that the data represent only normal transmittance. Radiation scattered into the cell can also lead to light-generated current, so that the measured values represent a minimum flux that could actually be absorbed by the cell. Moreover, most of the flux not transmitted is represented by reflection at the surfaces, not by absorption. The thicknesses of the materials represent those easily obtainable from commercial sources. (Material development was not in the scope of this program.)

"Teflon" FEP

Compared with the rest of the materials evaluated, "Teflon" FEP alone gives rather high transmittance in both the long (7000 to 12,000 A) and short (3000 to 7000 A) wavelength ranges. Likewise, it exhibits low sensitivity to UV degradation, at least in the short wavelength range, as expected. (Results are given in Table 32.)

TABLE 32. NORMAL LIGHT TRANSMITTANCE OF POLYMER FILMS AND FILM/ADHESIVE LAMINATES BEFORE AND AFTER EXPOSURE TO 2515 HOURS OF ULTRAVIOLET RADIATION (1 Sun)

Film			Adhesive			Transmittance Before UV Exposure[(a)]				After UV Exposure, 3000 to 7000 A(b,c)		Change due UV Exposure, 3000 to 7000 A	
	Thickness			Thickness		7000 to 12,000 A[(c)]		3000 to 7000 A[(c)]					
Type	µm	(mils)	Type	µm	(mils)	Percent	S.D.	Percent	S.D.	Percent	S.D.	Percent	S.D.
FEP Teflon	127	(5)	None	--	--	91.7	0.93	85.8	0.87	82.2	1.40	- 4.2	2.04
	127	(5)	Scotch-Weld 2216	76-102	(3-4)	82.2	1.28	62.7	1.96	59.8	0.81	- 4.6	2.57
	127	(5)	Silgrip-SR 573	25-51	(1-2)	90.4	1.98	83.8	2.12	73.1	4.31	-12.1	4.44
	127	(5)	Acryloid B-7	25-51	(1-2)	88.3	1.66	84.6	2.30	79.9	2.68	- 5.5	3.92
Tedlar	102	(4)	None	--	--	74.7	0.48	59.8	2.41	56.3	3.72	- 5.9	2.85
	102	(4)	Scotch-Weld 2216	76-102	(3-4)	76.6	1.15	50.4	1.24	54.6	3.26	+ 8.3	3.85
	102	(4)	Silgrip-SR 573	51	(2)	81.2	1.75	68.9	2.00	62.1	4.40	- 9.8	5.42
	102	(4)	Acryloid B-7	25-51	(1-2)	80.3	0.79	65.8	1.71	62.5	3.99	- 5.1	3.87
Halar	127	(5)	None	--	--	86.9	1.04	68.8	2.17	65.1	3.06	- 5.4	3.06
	127	(5)	Scotch-Weld 2216	76-102	(3-4)	82.3	0.77	56.8	0.71	56.9	1.76	+ 0.4	2.76
	127	(5)	Acryloid B-7	25-51	(1-2)	87.3	2.22	70.6	3.31	64.1	2.20	- 9.1	2.55
Sun-Lite[(d)]	635	(25)	None	--	--	16.7	3.70	14.1	2.48	11.8	4.00	-17.8	16.6
	635	(25)	Scotch-Weld 2216	76-127	(3-5)	18.9	5.04	13.6	3.19	12.1	5.08	-15.2	23.7
	635	(25)	Silgrip-SR 573	51-76	(2-3)	19.8	5.45	14.6	3.00	17.6	6.30	+18.1	23.4
Tuffak	508	(20)	None	--	--	89.2	0.71	81.5	1.64	66.3	0.61	-18.6	2.21
	508	(20)	Scotch-Weld 2216	76-102	(3-4)	82.2	2.65	62.5	1.94	58.5	2.41	- 6.4	5.14
	508	(20)	Acryloid B-7	25-76	(1-3)	82.9	2.64	78.0	4.38	63.1	0.86	-18.9	5.24
Acrylite	3175	(125)	None	--	--	89.3	0.67	75.9	1.39	70.0	1.04	- 7.8	1.46
	3175	(125)	Scotch-Weld 2216	102-127	(4-5)	81.6	1.53	62.1	2.28	63.1	2.09	+ 0.1	2.86
	3175	(125)	Silgrip-SR 573	51-76	(2-3)	86.5	2.07	68.9	1.10	68.4	1.79	- 0.6	3.85
	3175	(125)	Acryloid B-7	25-51	(1-2)	85.4	1.87	73.8	0.35	69.6	1.57	- 5.7	1.98
Flexigard	102	(4)	None	--	--	86.5	0.82	62.9	1.80	58.1	2.00	- 7.6	1.36
	102	(4)	Silgrip-SR 573	51-76	(2-3)	87.4	1.27	58.5	1.06	57.1	1.68	- 2.4	2.02

(a) Measurements made with Cary 14 spectrometer.

(b) Measurements made with Cary 118 spectrometer; values for Tedlar, Halar, and Sun-Lite corrected to Cary 14 data.

(c) Average of five samples.

(d) Low normal transmittance due to light scattering by glass fibers in Sun-Lite.

In the long wavelength range, and before UV exposure, none of the adhesives reduced the transmittance substantially; the largest reduction was caused by the epoxy adhesive Scotch-Weld 2216. A substantial reduction did occur for the epoxy adhesive in the low wavelength range. This result occurred for all sheet/film candidates. That is, the epoxy exhibits considerable absorption in the 3000 to 7000 A range.

The major effect of UV exposure in the short wavelength range was a 12 percent reduction in transmittance owing to the presence of the silicone adhesive Silgrip SR573.

Tedlar

The halocarbon, Tedlar, shows rather poor normal transmittance compared with that of the other sheet/films (with the exception of Sun-Lite which has lower normal transmittance), particularly in the 3000 to 7000 A range. Exposure to 2500 hours of UV radiation reduced the transmittance in this range by about 6 percent.

Without exception, the transmittance of Tedlar is increased with the application of an adhesive. This result clearly stems from improvement in optical coupling among the Tedlar/adhesive interfaces. Again, the application of Scotch-Weld 2216 adhesive leads to a decrease in transmittance in the short wavelength range. Exposure to UV radiation leads to a decrease in transmittance ranging from about 5 to 10 percent, except for Scotch-Weld 2216. Here an increase of 8 percent was manifest. Whether curing by UV was a cause for the increase is unknown but possible.

Halar

For Halar, another halocarbon, the transmittance in the long wavelength range is rather high, 87 percent, but rather low in the short wavelength range, 69 percent. Typical of the other halocarbons, the reduction due to UV exposure was about 5 percent.

Application of Scotch-Weld 2216 reduced the transmittance in both ranges, but, again, largely in the 3000 to 7000 A range. Acryloid B-7, an acrylic, increased the transmittance slightly. As with Tedlar, UV exposure increased (slightly) the transmittance with Scotch-Weld 2216/Halar.

Sun-Lite

The normal transmittance of Sun-Lite, a glass-reinforced polyester, is very low for the total wavelength range examined, primarily because of light scattering by the glass fibers. As expected, the addition of adhesive layers does not affect the transmittance much. UV exposure of Sun-Lite alone reduces transmittance substantially; comparable results are found with the Scotch-Weld/Sun-Lite laminate. Silgrip caused an increase, but as in all of these samples, the variability is large: note (in Table 32) the large values of the standard deviation. As discussed later, Sun-Lite does not decrease the light flux reaching a solar cell as much as indicated by the relatively low normal transmittance.

Tuffak

Tuffak, a polycarbonate, exhibits a comparatively high transmittance over the whole wavelength range. However, exposure to UV reduced the transmittance by approximately 19 percent. A comparable decrease was found with the Tuffak/Acryloid B-7 laminate under UV exposure. The reduction in the short wavelength range again shows up when Scotch-Weld 2216 is used.

Acrylite

Rather high transmittance is exhibited by Acrylite, an acrylic, in both wavelength ranges, especially the high range. About 8 percent reduction was found upon UV exposure. Changes in transmittance in the 3000 to 7000 A range are small for this material with all adhesives examined. Note (Table 32) the rather large thickness of the Acrylite employed.

Flexigard

Flexigard is a commercial laminate structure, probably an acrylic/polyester laminate. The film alone showed rather high transmittance in the 7000 to 12,000 A range, and a rather low value in the 3000 to 7000 A range. Direct comparison with the other polyester, Sun-Lite, is not fruitful because of the light-scattering effect in the latter material. An 8 percent reduction in transmittance was found which is attributable to UV exposure. With Silgrip SR573 adhesive, the reduction resulting from UV exposure was small.

Conformal Polymer Coatings – Effects of Encapsulation and Environmental Exposures on the Electrical Characteristics of Cells Encapsulated With These Coatings

In the LSA Project, to achieve the goal for low-cost photovoltaic arrays (as indicated in the Introduction), one of the important areas for reducing costs is the array (module) processing; it is presumed that automatic processing will be employed. If a conformal coating of a polymer material would suffice for the encapsulation requirements, significant cost reductions could be realized. To evaluate this possibility, two types of conformal coatings were applied to individual cells and their electrical characteristics measured before and after encapsulation and before and after exposure to artificial environments. On the basis of Phase I results, the two coatings chosen for evaluation were Eccocoat AC-8, an acrylic, and DC 3140 (1204 Primer), a silicone (see Table 4).

Three sets of five cells each were prepared for each of these two coating materials so that more than one type of exposure could be run simultaneously. Identification of the cell numbers (internal numbering system) and the coating weights applied are presented in Table 33. The average weight per unit area for the acrylic coating (Eccocoat) was 9.73 mg-cm^{-2}; the standard deviation was 0.73 mg-cm^{-2}. Corresponding values for the silicone coating (DC 3140) were 28.1 and 3.21 mg-cm^{-2}. The exposures were:

(1) Ultraviolet radiation, 1994 hours, 1 sun (Table 34)

(2) High humidity, 97 percent R.H., 38 C (Table 35)

(3) Temperature cycling, -40 to 90 C, 56 cycles, plus 1000 hours high humidity (Table 36).

TABLE 33. WEIGHTS OF CONFORMAL COATINGS APPLIED TO SOLAR CELLS

Cell	Weight, mg-cm^{-2}	Cell	Weight, mg-cm^{-2}
Eccocoat AC-8, Acrylic(a)		DC3140 Silicone, DC1204 Primer(b)	
138	9.6	155	31.2
139	9.3	156	31.6
140	9.8	158	22.9
141	9.7	159	21.7
142	9.2	160	26.7
143	10.4	161	29.8
144	10.0	162	25.6
145	10.0	163	28.8
146	9.9	164	30.6
147	8.9	165	26.1
150	9.9	166	26.8
151	11.5	167	27.9
152	10.3	168	33.6
153	8.8	169	28.8
154	8.6	118	28.6

(a) Average 9.73; S.D., 0.73.

(b) Average 28.05; S.D., 3.21.

TABLE 34. CHANGES IN ELECTRICAL CHARACTERISTICS OF CONFORMALLY COATED CELLS AFTER ENCAPSULATION AND AFTER EXPOSURE TO ULTRAVIOLET RADIATION[(a)]

Coating	V_{oc}			I_{sc}			P_{max}			F.F.			R_{sh}			R_s		
	N	Δ,%	S.D.(b)	N	Δ,%	S.D.	N	Δ,%	S.D.	N	Δ,%	S.D.	N	Δ,%	S.D.	N	Δ,%	S.D.
Eccocoat AC-8(c)																		
Encapsulation	5	-3.73	0.90	5	-1.08	0.99	5	-7.53	1.17	5	-3.06	1.11	5	131	46.1	5	36.7	7.26
UV, 1994 hours	5	3.04	1.33	5	-1.38	0.49	5	-2.54	5.31	5	-4.12	4.32	5	14.3	8.52	5 4	13.2 -2.82	22.0 0.79(d)
DC 3140/1204 Primer(e)																		
Encapsulation	5	1.23	0.36	5	2.11	0.59	5	-1.92	2.20	5	-6.87	4.32	5	12.7	56.2	5	17.7	27.3
UV, 1994 hours	5	-2.32	0.65	5	-9.89	2.06	5	-14.2	4.99	5	-1.26	5.71	5	-6.00	10.9	5	45.3	49.3

(a) Radiation approximately 1 sun.

(b) N is number of cells in group; Δ,% is average fractional change x 100 of indicated parameters: for "encapsulation" the base is the "as-cleaned value"; for "UV" the base is the "encapsulation" value; S.D. stands for standard deviation.

(c) Cells 150, 151, 152, 153, and 154.

(d) Values with an "outliner" removed. Some outliners are removed in subsequent tables. In all cases, the values are also given without removing the outliners.

(e) Cells 166, 167, 168, 169, and 118.

TABLE 35. CHANGES IN ELECTRICAL CHARACTERISTICS OF CONFORMALLY COATED CELLS AFTER ENCAPSULATION AND AFTER EXPOSURE TO HIGH-HUMIDITY ENVIRONMENT[(a)]

Coating	V_{oc}		[(b)]	I_{sc}			P_{max}			F.F.			R_{sh}			R_s		
	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.
Eccocoat AC-8[(c)]																		
Encapsulation	4	−4.46	1.15	4	1.70	1.03	4	−5.93	2.37	4	−3.16	2.35	4 3	82.4 30.2	106 23.7	4	40.8	19.8
1000 hours H.H.	5	2.88	1.76	5	−5.51	0.52	5	−14.8	6.19	5	−9.74	7.44	5	3.12	3.34	5	44.1	41.0
DC 3140/1204 Primer[(d)]																		
Encapsulation	5	1.16	1.19	5	1.56	1.15	5	−1.21	6.06	5	−3.62	3.81	5	2.93	5.23	5	7.80	11.3
1000 hours H.H.	5	−2.06	0.57	5	−5.46	0.47	5	−17.6	7.11	5	−11.0	7.33	5	0.06	7.59	5	50.7	38.4

(a) 97 percent relative humidity, 38 C.

(b) N is number of cells in group; Δ, % is average fractional change X 100 of indicated parameters; for "encapsulation" the base is the "as-cleaned" value; for "H.H." the base is the "encapsulation" value; S.D. stands for standard deviation.

(c) Cells 138, 139, 140, 141, and 142; "as-cleaned" value for Cell 138 not available.

(d) Cells 155, 156, 158, 159, and 160.

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TABLE 36. CHANGES IN ELECTRICAL CHARACTERISTICS OF CONFORMALLY COATED CELLS AFTER ENCAPSULATION, AFTER TEMPERATURE CYCLING, AND AFTER EXPOSURE TO HIGH-HUMIDITY ENVIRONMENT

Coating	V_{oc}			I_{sc}			P_{max}			F.F.			R_{sh}			R_s		
	N	Δ, %	S.D.[a]	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.
Eccocoat AC-8																		
Encapsulation	5	-2.68	0.93	5	2.04	0.73	5	-6.85	4.54	5	-6.63	4.02	5	280	381	5 4	216 40.0	394 16.9
T.C. (56 cycles)[b][c]	4	0.76	0.80	4	-5.00	1.62	4	-24.7	15.9	4	-21.6	16.0	4	0.37	8.18	4	77.8	49.0
T.C. + 1000 hours H.H.[d]	4	-0.89	0.81	4	-4.58	2.58	4	-34.7	11.9	4	-30.9	12.0	4	-5.10	27.6	4	116	40.9
DC 3140/1204 Primer																		
Encapsulation	4	2.23	0.95	4	1.75	0.47	4	-1.26	2.26	4	-5.07	1.81	3	47.4	56.4	5 4	24.9 39.5	35.5 15.9
T.C. (56 cycles)[e]	5	-1.79	2.48	5	-4.42	2.02	5	-22.3	9.00	5	-17.6	9.95	5	10.9	60.1	5	117	72.9
T.C. + 1000 hours H.H.	4	-2.94	0.48	4	-3.22	2.34	4	-34.9	12.3	4	-31.0	12.3	4	8.14	64.5	5	225	91.8

(a) N is number of cells in group; Δ, % is average fractional change X 100 of indicated parameters: for "encapsulation", the base is the "as-cleaned" value; for T.C. and T.C. + 1000 hours H.H., the base is the "encapsulation" value; S.D. stands for standard deviation.

(b) Cycling between -40 and 90 C on 4-hour cycle; humidity not controlled; 336 hours or 84 cycles.

(c) Cells 143, 144, 145, 146, and 147; Cell 145 developed or solder joint; Cell 146 had crack.

(d) H.H. stands for high humidity: 38 C and 97 percent relative humidity

(e) Cells 161, 162, 163, 164, and 165.

For purposes of discussion, the effects of encapsulation alone on the electrical characteristics of cells are addressed first; the effects of the various exposures are discussed in subsequent sections.

Effects of Encapsulation

The effects of encapsulation with conformal coatings are shown, along with results after exposure for the same encapsulated cells, in Tables 34, 35, and 36. In regard to the (initial) effects of encapsulation, the "Δ,%" notation means the percentage change from the "as-cleaned" condition of the cell as the base. Cleaning procedures are discussed in the first part of this report.

Eccocoat AC-8. As noted in Tables 34, 35, and 36, encapsulation with the Eccocoat AC-8 acrylic coating leads to a decrease of approximately 7 percent in the maximum power, P_{max}, obtained from the cells. The origin of the decrease is found in an increase in the series resistance, R_s. The short-circuit current, I_{sc}, is little affected. Since shunt resistance, R_{sh}, is increased, the major effect apparently lies in the interactions between the coating and the metallization. Thus, the effects of encapsulation with the coating are substantial and serious.

DC 3140/1204 Primer. Compared with the Eccocoat acrylic coating, the silicone coating (DC 3140) has much smaller effects on P_{max} upon encapsulation. The reduction in P_{max} is less than 2 percent, on the average. V_{oc} is not reduced. R_{sh} is increased, but not to the same extent as for the acrylic coating. An increase in R_s is evident and significant, but is less than the average value for the acrylic coating. Note the rather high variability of the values as reflected in the standard deviations. Note also that, as previously stated, some of the variability is reflected in the original condition of the cells before encapsulation. That is, all the variability cannot be attributed to encapsulation alone. It was not possible to select cells that would mitigate this type of variability. Nevertheless, it is clear that further study of processing variables in applying such coatings is needed to enable reduction of the variability.

Effects of Ultraviolet Radiation

The term "Δ,%" for encapsulated cells after UV exposure in Table 34 denotes the average percentage change from the "encapsulated" values so as to single out the effects of UV alone. As before, considerable variability exists in R_{sh} and R_s. Where appropriate, Δ,% is averaged for less than the total number of cells in the group to point out that an "outliner" exists. In all cases, the average for the total number of cells is presented.

Eccocoat AC-8. Approximately 2000 hours of UV radiation (1 sun) has a rather small effect – less than 3 percent on the average – on P_{max} of cells encapsulated with the Eccocoat AC-8 acrylic coating. Some of this decrease stems from a reduction in I_{sc}. Except for an "outliner", R_s decreased. The significant increase in V_{oc} is unexplained, although it should be noted that the cell temperature is difficult to control in these measurements when the cell is encapsulated. The control on these measurements is the temperature control on the copper platen on which the cell rests.

DC 3140/1204 Primer. A rather large average decrease in P_{max} (14 percent) was found for cells encapsulated with the DC 3140 silicone coating after exposure to UV radiation. This decrease arises from a decrease in V_{oc} and I_{sc} and a significant increase in R_s. This latter value is highly variable, as noted in Table 34.

Effects of High Humidity

If, as expected, interaction of the environment with the metallization is an important effect with silk-screened electrodes, exposure to high-humidity environments should affect the power output substantially. This result was found for the cells with conformal coatings.

Eccocoat AC-8. Exposure of Eccocoat-coated cells for 1000 hours in a chamber with a relative humidity of 97 percent (at 38 C) leads to a decrease in P_{max} of approximately 15 percent. A decrease in I_{sc} contributed to this result, but the major effect is an increase in R_s, on the average. As in the case with UV radiation, V_{oc} increased for some as-yet unexplained reason.

DC 3140/1204 Primer. Under high-humidity exposure, the results obtained for this silicone coating were approximately the same as those obtained for the Eccocoat acrylic coating. A decrease in P_{max} of approximately 18 percent was measured, along with a large increase in R_s. V_{oc} decreased by 2 percent.

Effects of Temperature Cycling and High Humidity

One set of cells encapsulated with conformal coatings was exposed to temperature cycling (-40 to 90 C, 4-hour cycle period) and then to a high-humidity environment. The data are presented in Table 36. Since the humidity was not controlled under temperature cycling (T.C.), the T.C. exposure represents effects of water vapor also.

Eccocoat AC-8. Fifty-six cycles of temperature excursions reduced P_{max} by approximately 25 percent, due in part to a drop in I_{sc} but primarily due to a large increase in R_s. The effects of water vapor probably overshadowed the temperature cycling per se. Further exposure to a high-humidity environment further decreased I_{sc} and increased R_s. P_{max} decreased by approximately 35 percent for the total exposure. (The "encapsulated" value is the base for both exposures.)

DC 3140/1204 Primer. The effects of the dual exposures generated equal reductions in P_{max} for both this silicone coating and the Eccocoat acrylic coating, that is, a P_{max} reduction of approximately 35 percent. The origins of the reduction likewise are essentially the same, although there are rather small differences in the response of I_{sc} and V_{oc} for the two coatings, as noted in Table 35.

Comparative Effects of Environmental Exposures

On the basis of these data on conformal polymer coatings commercially available, clearly they do not represent sufficient protection from expected service environments. Although no detailed physical evaluation of the cells was possible in this program, the principal area of susceptibility is the interaction of water vapor with the metallization/silicon interface. Temperature cycling by itself produced only one possible cracked cell. Relatively short-time UV exposure had smaller effects, as expected from the choice of coatings. So the sensitive exposure is water vapor, and the major consequence is the large increase in series resistance. Typical effects of exposure on the electrical characteristics of a conformally coated cell are shown in Figure 11.

Polymer Sheet/Film Materials – Effects of Encapsulation and Environmental Exposures on Electrical Characteristics of Cells Encapsulated With These Materials (Laminates)

As in the case of conformal coatings, individual solar cells were encapsulated. In this part of the investigation, preformed polymer sheets or films were employed as cover materials and adhered to the cell with either Scotch-Weld 2216 or Silgrip SR573 adhesives. The bottom cover was either a polymer sheet/film or aluminum foil [76.2 μm (3 mils)], and was adhered to the cell back with one of the adhesives mentioned. Thus, the laminates consisted of the following structure: front cover/adhesive/cell/adhesive/back cover. Note that the adhesives at the edge of the structure were exposed to the environment. The thicknesses of the polymer sheet/films are given in the second column of Table 32. On the basis of previous results (Phase I), the following polymer sheet/film materials were chosen for further investigation:

- Sun-Lite (GR polyester)
- Acrylite (acrylic)
- Teflon FEP (halocarbon)
- Flexigard (acrylic-polyester laminate).

The changes in electrical characteristics following encapsulation and following exposure to the environmental stresses are given in Tables 37, 38, and 39.

Effects of Encapsulation

As in previous data, the effects of encapsulation are expressed as percentage changes from the as-cleaned cell characteristics. The average change and the corresponding standard deviation for each of the three sets of cells used in this part of the investigation are given in Tables 37, 38, and 39. For comparison, the data for the three sets were pooled for P_{max}. The pooled data are given in Table 40. In this pooling, standard formulas were used to estimate the average P_{max} and the pooled standard deviation from the averages and standard deviation from each set. Outliners were excluded from this pooling; these are noted in the tables.

As can be seen from Table 40, the pooled value of P_{max} for the Sun-Lite laminates decreased somewhat, but exhibited high variability. Even so, it is clear that the decrease in P_{max} did not reflect the very low normal transmittance measured previously (see Table 32). Considerable light is scattered into the silicon cell. Some reduction in P_{max} is attributable to an increase in R_s for these laminates; small effects on I_{sc} were observed.

CELL 163

Element	Material	Thickness, in.
Top Cover	DC3140, 1204 Primer	0.003
Adhesive	None	
Cell	Si; Silk-Screened Ag	0.012
Adhesive	None	
Bottom Cover	DC3140, 1204 Primer (on GPO-3, 1/8" Backing)	0.003

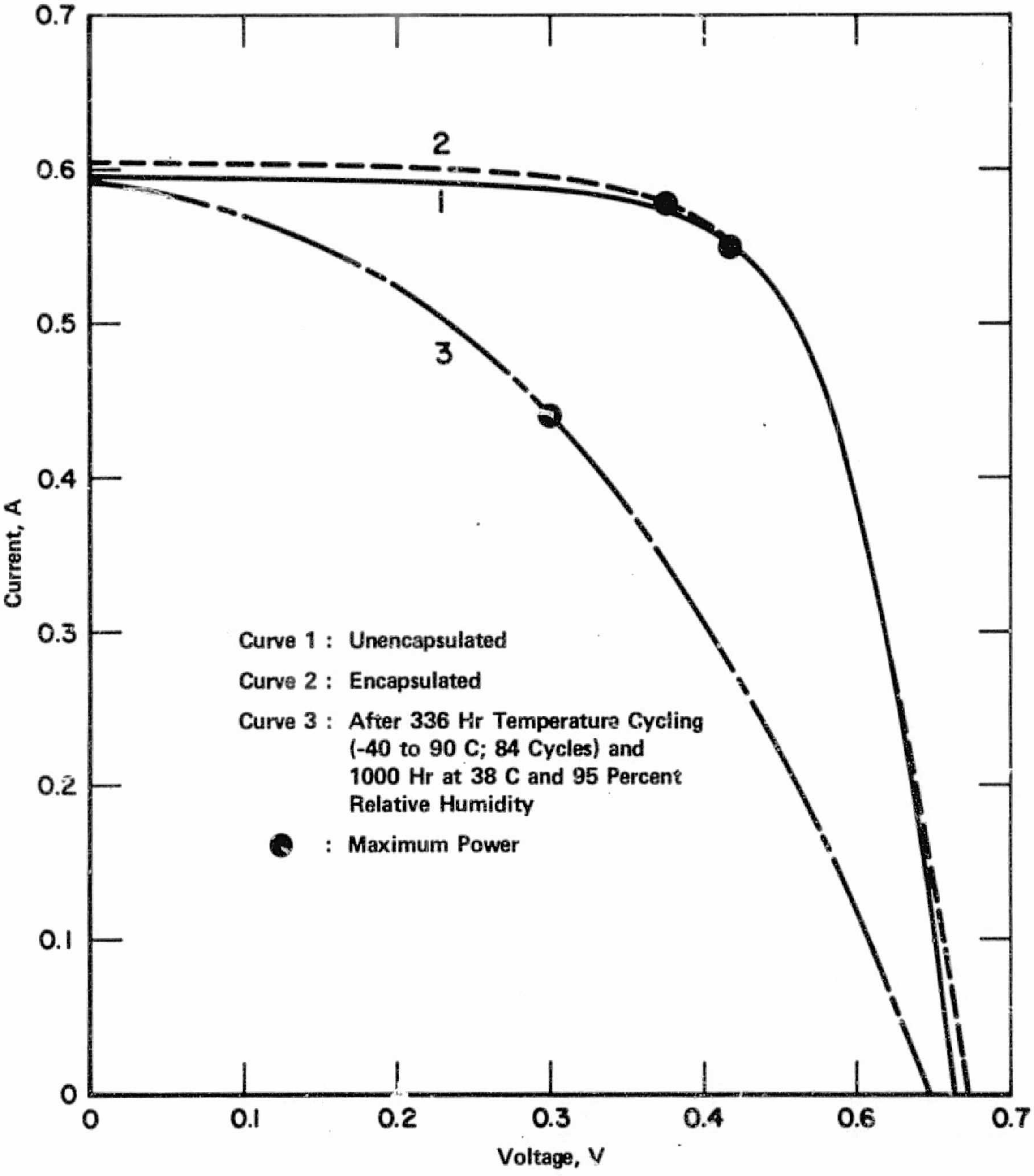

FIGURE 11. ELECTRICAL CHARACTERISTICS OF A CONFORMALLY COATED CELL BEFORE AND AFTER SELECTED EXPOSURES

TABLE 37. CHANGES IN ELECTRICAL CHARACTERISTICS OF CELLS ENCAPSULATED WITH POLYMER SHEET/FILM MATERIALS AFTER ENCAPSULATION AND AFTER EXPOSURE TO 1444 HOURS OF ULTRAVIOLET RADIATION (APPEOXIMATELY 1 SUN)

Laminate	V_{oc}			I_{sc}			P_{max}			F.F.			R_{sh}			R_s		
	N	Δ, %	S.D.(a)	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.
Sun-Lite/Scotch-Weld 2216/cell/Scotch-Weld 2216/Al foil(b)																		
Encapsulation	5	0.38	2.26	5	-1.63	4.77	5	- 3.83	12.0	5	-2.48	10.1	5	7.17	8.36	5	8.7	36.0
UV	4	0.54	0.58	4	-7.88	9.61	4	-10.2	24.8	4	-3.99	19.2	3	18.5	5.35	4	130	198
																3	31.2	21.0
Acrylite/Scotch-Weld 2216/cell/Scotch-Weld 2216/Al foil(c)																		
Encapsulation	5	-0.03	0.88	5	3.55	1.52	5	1.39	1.48	5	-2.04	0.76	5	86.8	180	5	4.04	15.6
UV	5	-0.42	0.44	5	-0.85	0.92	5	-0.32	1.50	5	1.52	0.06	5	12.8	21.5	5	44.9	10.8
Flexigard/Silgrip SR573/cell/Silgrip SR573/Flexigard(d)																		
Encapsulation	5	-0.63	1.11	5	-0.30	1.21	5	-7.74	0.90	5	-7.26	2.18	5	93.4	145	5	39.9	19.7
UV	5	0.01	0.98	5	1.02	0.69	5	0.68	2.29	5	0.02	1.11	5	-0.60	1.77	5	21.1	13.9
Teflon FEP/Silgrip SR573/cell/Silgrip SR573/Teflon FEP(e)																		
Encapsulation	5	0.25	0.68	5	3.06	0.56	5	0.41	1.44	5	-2.82	1.43	5	6.70	10.9	5	16.7	15.2
UV	5	-0.21	0.58	5	0.67	0.50	5	0.42	0.67	5	0.00	1.00	5	-3.28	6.16	5	38.0	46.5
Sun-Lite/Silgrip SR573/cell/Silgrip SR 573/Al foil(f)																		
Encapsulation	5	-0.03	0.15	5	0.68	2.19	5	-2.45	1.90	5	-3.16	2.18	5	-2.97	4.52	5	0.30	30.9
U.V.	5	0.03	0.83	5	-5.05	10.8	5	-6.26	12.3	5	-1.47	3.18	5	-33.1	59.1	5	36.4	18.1
	3	-0.18	1.06	3	0.50	1.65	3	0.68	3.74	3	0.53	2.29	3	9.97	3.89			

(a) N is number of cells in group; Δ,% is average fractional change X 100 of indicated parameters: for "encapsulation" the base is the "as-cleaned" value; for "UV" the base is the encapsulation value; S.D. stands for standard deviation.

(b) Cells 277, 278, 279, 280, and 281.

(c) Cells 263, 265, 266, 268, and 269.

(d) Cells 170, 173, 174, 176, and 177.

(e) Cells 188, 189, 190, 191, and 192.

(f) Cells 238, 239, 253, 256, and 211.

TABLE 38. CHANGES IN ELECTRICAL CHARACTERISTICS OF CELLS ENCAPSULATED WITH POLYMER SHEET/FILM MATERIALS AFTER ENCAPSULATION AND AFTER EXPOSURE TO HIGH-HUMIDITY ENVIRONMENT (97 PERCENT RELATIVE HUMIDITY, 38 C)

Laminate	V_{oc}			I_{sc}			P_{max}			F.F.			R_{sh}			R_s		
	N	Δ, %	S.D.[a]	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.
Sun-Lite/Scotch-Weld 2216/Cell/ Scotch-Weld 2216/Al foil[b]																		
Encapsulation	5	1.07	0.62	5	1.71	2.12	5	0.91	1.90	5	-1.82	1.30	5	5.47	5.14	5	-0.88	13.7
H.H.	5	-1.51	0.37	5	-14.4	3.53	5	-17.9	3.99	5	-2.56	3.00	5	9.73	7.88	5	84.2	49.4
Acrylite/Scotch-Weld 2216/Cell/ Scotch-Weld 2216/Al foil[c]																		
Encapsulation	5	-0.35	0.49	5	1.90	0.66	5	-0.53	1.14	5	-2.12	1.37	5 4	10.4 9.35	44.6 6.87	5	-10.8	12.8
H.H.	5	-0.42	0.27	5	1.36	0.39	5	-0.61	1.83	5	-1.51	1.52	5	1.83	5.25	5	55.1	32.0
Flexigard/Silgrip SR573/Cell/ Silgrip SR573/Flexigard[d]																		
Encapsulation	4	-0.05	0.42	4 3	-4.71 -2.13	5.54 2.41	4 3	-8.54 -6.32	4.51 0.86	4 3	-3.56 -2.40	2.41 0.80	4 3	26.0 0.24	51.5 2.22	4	15.8	20.4
H.H.	4	-0.05	0.17	4	2.32	0.45	4	-2.81	1.11	4	-5.20	0.84	4	7.25	10.4	4	48.1	11.6
Teflon FEP/Silgrip SR573/Cell/ Silgrip SR573/Teflon FEP[e]																		
Encapsulation	5 3	-0.20 0.59	1.15 0.20	5 3	-5.25 1.78	9.68 0.92	5 3	-7.61 0.89	13.5 0.77	5 3	-2.70 -0.99	7.54 2.24	5	14.9	16.4	5	19.3	26.9
H.H.	5	-0.35	0.35	5	1.20	2.65	5	-5.63	5.39	5	-6.50	3.26	5	-4.02	12.4	5	76.7	27.3
Sun-Lite/Silgrip SR573/Cell/ Silgrip SR573/Al foil[f]																		
Encapsulation	4	0.40	0.39	4	-2.89	2.86	4	-6.69	3.08	4	-4.69	3.89	4	2.18	12.4	4	9.8	34.4
H.H.	4	-0.44	0.59	4	-7.19	2.68	4	-21.4	12.3	4	-14.3	13.2	4	7.08	9.50	4	216	217

(a) N is number of cells in group; Δ, % is average fractional change X 100 of indicated parameters: for "encapsulation" the base is the "as-cleaned" value; for "H.H." the base is the "encapsulation" value; S.D. stands for standard deviation.

(b) Cells 287, 288, 289, and 292.

(c) Cells 272, 273, 274, 275, and 276.

(d) Cells 185, 247, 248, and 249.

(e) Cells 199, 205, 206, 207, and 251.

(f) Cells 236, 241, 242, and 244.

TABLE 39. CHANGES IN ELECTRICAL CHARACTERISTICS OF CELLS ENCAPSULATED WITH POLYMER SHEET/FILM MATERIALS AFTER ENCAPSULATION AND AFTER TEMPERATURE CYCLING(a) PLUS EXPOSURE TO HIGH-HUMIDITY ENVIRONMENT(b)

Laminate	V_{oc}			I_{sc}			P_{max}			F.F.			R_{sh}			R_s		
	N	Δ, %	S.D.(c)	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D.	N	Δ, %	S.D
Sun-Lite/Scotch-Weld 2216/Cell/ Scotch-Weld 2216/Al foil(d)																		
Encapsulation	5	-0.28	0.30	5	1.76	1.61	5	3.24	5.46	5	1.22	4.65	5	8.12	1.57	5	16.9	18.1
T.C. and H.H.	5	0.32	0.39	5	-16.7	4.26	5	-21.3	4.46	5	-5.48	6.60	5	21.0	18.5	5	63.2	27.0
Acrylite/Scotch-Weld 2216/Cell/ Scotch-Weld 2216/Al foil(e)																		
Encapsulation	5	-0.17	1.00	5	2.13	1.34	5	-0.09	2.26	5	-2.06	0.87	5	5.94	2.51	5	-11.9	5.02
T.C.(f)								DELAMINATED										
Flexigard/Silgrip SR573/Cell/ Silgrip SR573/Flexigard(g)																		
Encapsulation	5	-0.66	1.16	5	-2.87	5.37	5	-8.84	8.50	5	5.99	2.43	5	8.83	31.2	5	13.8	22.1
				3	0.28	0.35	4	-5.07	1.14									
T.C. and H.H.	5	0.35	0.30	5	-1.83	8.43	5	-12.5	6.49	5	-10.3	11.0	5	5.26	9.04	5	107	33.4
				3	2.16	0.64												
Teflon FEP/Silgrip SR573/Cell/ Silgrip SR573/Teflon FEP(h)																		
Encapsulation	5	0.88	0.33	5	3.24	1.13	5	5.24	6.47	5	-1.43	1.04	5	-0.66	21.6	5	24.7	36.8
T.C. and H.H.(i)	2	-1.06	0.25	2	1.12	2.77	2	-18.8	21.3	2	-19.7	19.2	2	21.7	29.4	2	101	105
Sun-Lite/Silgrip SR573/Cell/ Silgrip SR573/Al foil(j)																		
Encapsulation	4	-0.62	0.84	4	-11.2	18.5	4	-15.2	19.8	4	-4.27	3.67	4	0.26	7.17	4	41.4	48.5
				3	-2.01	3.48	3	-5.43	4.23	3	-2.46	0.81						
T.C. and H.H.(k)	2	-0.52	0.74	2	-5.72	0.72	2	-22.8	9.52	2	-17.6	10.5	2	12.1	4.08	2	197	51.0

(a) 240 hours temperature cycling -40 to 90 C, 60 cycles.
(b) 1096 hours at 97 percent relative humidity, 38 C.
(c) N is number of cells in group; Δ, % is average fractional change X100 of indicated parameters: for "encapsulation" the base is the "as-cleaned" value; for T.C. and H.H. the base is the "encapsulation" value; S.D. stands for standard deviation.
(d) Cells 282, 283, 284, 285, and 286.
(e) Cells 262, 264, 267, 270, and 271
(f) Encapsulation delaminated on temperature cycling.
(g) Cells 178, 180, 182, 183, and 184.
(h) Cells 186, 194, 195, 196, and 197.
(i) Cells 194, 196, and 197 cracked.
(j) Cells 208, 209, 243, and 261.
(k) Cell 208 cracked: Cell 209 had defective solder joint.

TABLE 40. POOLED AVERAGE CHANGE AND STANDARD DEVIATION FOR POWER MAXIMUM OF CELLS ENCAPSULATED WITH POLYMER SHEET/ FILM MATERIALS(a)

Laminate	Δ, % (Pooled Avg.)	Standard Deviation
Sun-Lite/Scotch-Weld 2216/cell/ Scotch-Weld 2216/Al foil	- 0.11	7.12
Acrylite/Scotch-Weld 2216/cell/ Scotch-Weld 2216/Al foil	0.26	1.57
Flexigard/Silgrip SR 573/cell/ Silgrip SR 573/Flexigard	- 7.09	0.89
Teflon FEP/Silgrip SR 573/cell/ Silgrip SR 573/Teflon FEP	2.38	3.84
Sun-Lite/Silgrip SR 573/cell. Silgrip SR 573/Al foil	- 4.61	2.67

(a) Some "outliners" omitted; see text.

Increases in P_{max} for Acrylite and Teflon FEP laminates upon encapsulation were the result of high transmittance and improved optical coupling. Although the reason is not clear, the use of Acrylite does not increase the series resistance in any substantial way; in fact, in two sets of cells, R_s decreased. With Teflon FEP, R_s increased approximately 20 percent on the average.

For the Flexigard laminates, encapsulation decreased P_{max} by approximately 7 percent, with low variability (omitting an "outliner"). This reduction apparently stems from low transmittance, especially in the short wavelength range (Table 32), and from increases in series resistance.

Effects of Ultraviolet Radiation

For cells laminated with the selected polymer film or sheet encapsulants, changes in the electrical characteristics as a result of 1444 hours of UV radiation (approximately 1 sun) are presented in Table 37. In the discussion below, the laminates are identified by the top cover.

Sun-Lite Laminates. UV radiation lowered P_{max} in the Sun-Lite laminates (both those made with the Scotch-Weld adhesive and those with the Silgrip adhesive) more than any other laminates. Sizable decreases occurred in both I_{sc} and R_s. UV radiation decreased the transmittance of the Sun-Lite/Scotch-Weld combination, but the opposite occurred for the Sun-Lite/Silgrip combination (see Table 32). Thus, much of the effect must be attributed to an R_s increase.

Acrylite Laminates. As expected, the effect of UV radiation on P_{max} of the acrylic laminates was small. However, a sizable increase in R_s was noted, but this increase had little effect on the fill factor. Likely, the magnitude of R_s is small on the average.

Flexigard Laminates. The effects of UV radiation on the Flexigard laminates were small. Most notable was an increase in R_s.

Teflon FEP Laminates. UV radiation effects on the Teflon FEP laminates were, likewise, small, except for an increase in R_s.

Effects of High-Humidity Environment

A set of laminates was exposed for 1000 hours to an air environment characterized by 95 percent relative humidity and a temperature of 38 C. The changes in electrical characteristics are presented in Table 38 for the various polymer film/sheet materials investigated.

Sun-Lite Laminates. As with UV radiation exposure, the high-humidity environment decreased P_{max} for the Sun-Lite laminates more than for any other. Degradative changes in I_{sc} and R_s were the cause.

Acrylite Laminates. Small effects were found on P_{max}. A substantial increase in R_s occurred.

Flexigard Laminates. A relatively small change in P_{max} was noted. Again the origin of degradation lies principally in an increase in R_s.

Teflon FEP Laminates. A 5.6 percent decrease in P_{max} occurred; again, R_s increased substantially.

So in sum, except for Sun-Lite, the principal assignment of degradation owing to the high-humidity environment is the interaction of water with the silk-screened metallization.

Effects of Temperature Cycling Plus High Humidity

A separate set of cell laminates were first exposed to 240 hours of temperature cycling (-40 to 90 C in a 4-hr cycle) and then placed in a high-humidity environment for 1096 hours (38 C). Electrical changes (Table 39) represent the effects of the combined exposures. The temperature-cycling data alone are not given because they were found to be in error owing to undetected changes in the standard light levels.

Sun-Lite Laminates. Consistently, the Sun-Lite laminates showed the largest degradation of the group in P_{max}. Decreases in I_{sc} and increases in R_s again were the causes. One cell of the Sun-Lite/Silgrip set developed a crack, and another developed a defective solder joint.

Acrylite Laminates. Under temperature cycling, the Acrylite laminates delaminated owing to poor bonding and/or to differences in expansion coefficients. Therefore, after the combined exposure no cell data were available.

Flexigard Laminates. P_{max} decreased substantially (12.5 percent) for the Flexigard laminates. A large increase in R_s was the principal cause. As noted in Table 39, large variations in I_{sc} occurred in the set.

Teflon FEP Laminates. Three of the five cells used in the Teflon FEP laminates were found to be cracked after the combined exposure. Likely, the cracks occurred during temperature cycling. A sizable decrease in P_{max} occurred, along with a large increase in R_s on the average. But the number of cells left in the set was too small to provide significant data.

Comparative Effects of Environmental Exposures

With regard to the total effects of the three environments, the largest effect of the high-humidity environment is on series resistance. UV radiation, to the extent of exposure used in this investigation, has only small effects. Temperature cycling leads to delamination in the acrylic laminates and to cracked cells in the Teflon FEP laminates. An example of the type of data taken on the polymer-laminated cells is shown in Figure 12. The major effects for the different polymer film and sheet materials investigated are summarized in Table 41. Aside from the noted delamination and cracked cells, the origin of the reduction in P_{max} is almost universally an increase in series resistance, evidently due to corrosion of the silk-screened silver metallization.

TABLE 41. GENERAL EFFECTS OF ENVIRONMENTAL EXPOSURE ON CELLS LAMINATED WITH POLYMER FILM/SHEET MATERIALS

Laminate	Degradative Exposure	Effect on P_{max}	Origin of Changes
Sun-Lite	All	Large	$-I_{SC}$; $+ R_S$
Acrylite	T.C.	Delaminated	
Flexigard	T.C. + H.H.	Large	$+R_S$
Teflon FEP	T.C.	Moderate	$+R_S$, Cracked cells

Glasses – Effects of Environmental Exposures on the Electrical Characteristics of Cells Encapsulated With Glasses

Description and Effects of Glass Encapsulants

In this phase of the investigation, solar cells were encapsulated with three types of glasses, using two adhesives. The glasses were soda-lime float, borosilicate (Corning 7740), and Sunadex B. Sunadex is a soda-lime glass with low iron content which leads to an increase in the transmittance, particularly in the long wavelength range of the solar spectrum. In fabricating these samples, the cells were laminated between two pieces of glass (glass was the top cover and the substrate) using polymer adhesive/pottants, as described previously in the report. The adhesives used in the fabrication were the silicone gel, Q3-6527, and the silicone, Sylgard 184 (see Table 4). In contrast to the Phase I studies, these glass laminates were edge-sealed with a lead tape.

The results of the earlier review of encapsulation experience(3,7), as well as the Phase I results, prompted the recommendation of glasses as prime candidates for encapsulation of solar cells, particularly for near-term application. Degradation of the glasses themselves will, of course, be very low in most environments to be encountered. It was found that borosilicate glasses, as represented by Corning 7740, performed well with regard to the optical coupling and transmittance (Tables 29 and 30). I_{SC} is increased by about 5 to 7 percent upon encapsulation. The high transmittance of the low-iron glasses results in similar favorable effects. Soda-lime float glass ("window glass") has significantly lower transmittance [and cost(3)] than the borosilicate or low-iron glasses but still provides good performance, with the I_{SC} for the cell after encapsulation being maintained at essentially the same level as the I_{SC} for the unencapsulated cell.

CELL 180

Element	Material	Thickness, in.
Top Cover	Flexigard	0.005
Adhesive	Silgrip SR573	0.006
Cell	Si; Silk-Screened Ag	0.012
Adhesive	Silgrip SR573	0.006
Bottom Cover	Flexigard	0.005

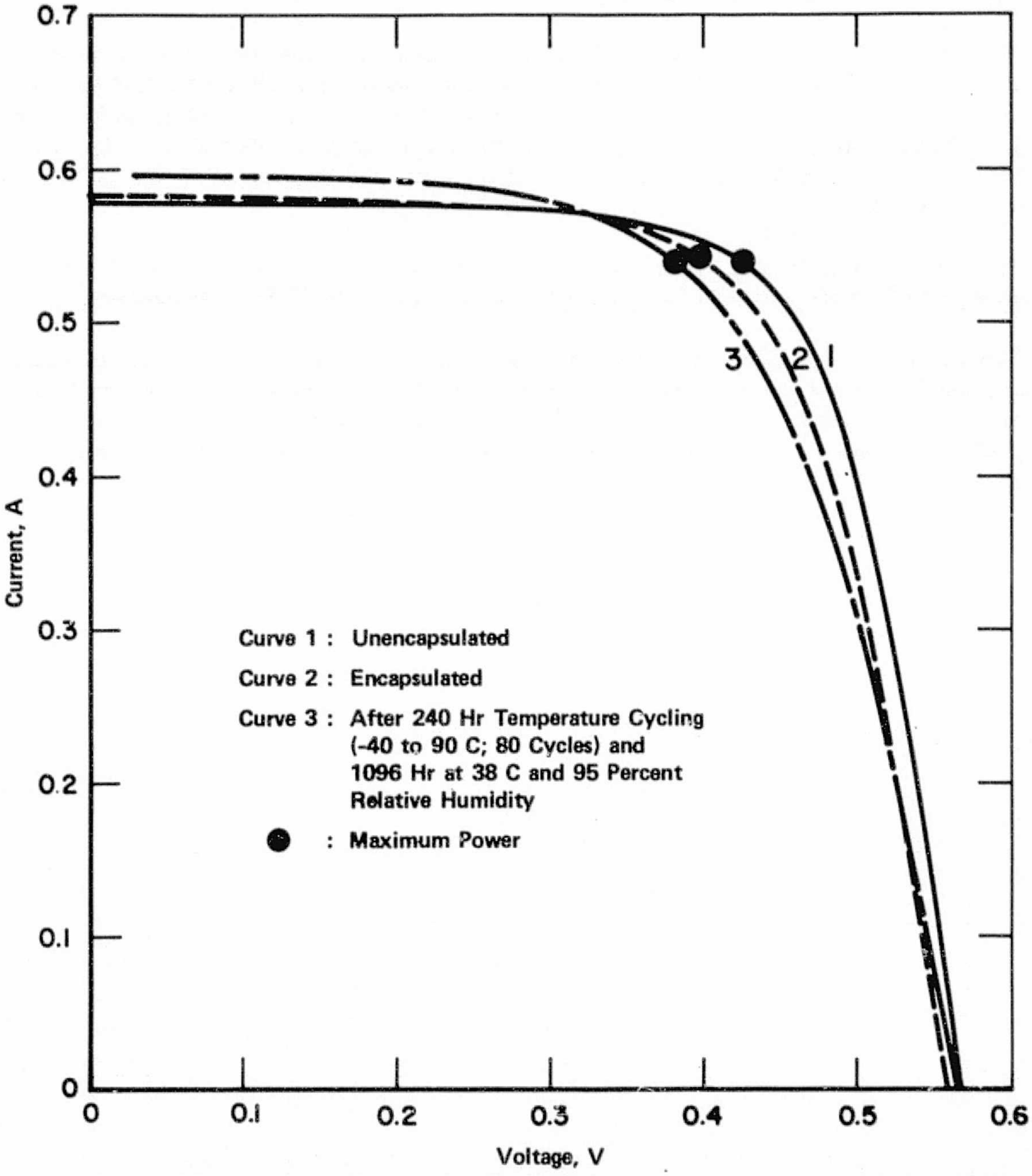

FIGURE 12. ELECTRICAL CHARACTERISTICS OF CELL ENCAPSULATED (LAMINATED) WITH FLEXIGARD FILM BEFORE AND AFTER EXPOSURE TO SELECTED ENVIRONMENTS

Effects of High Humidity, UV Radiation, and Temperature Cycling

The glass laminates were exposed late in the program and complete data on the electrical characteristics could not be obtained for separate types of exposures. The data in Table 42 represent the results after exposure to three types of environments, carried out separately and consecutively. The environments, characterized as high relative humidity, UV radiation, and temperature cycling, are defined in footnotes to the table. The base values used in calculating the percentage changes are the as-cleaned cell values. The replication of the samples fabricated is indicated in the footnotes to Table 42.

With regard to the results obtained (Table 42), a rather surprising result was the large increase in R_s for all laminates. Whether the increase came about during encapsulation or after exposure is not known. It is likely that the change occurred as a result of encapsulation, since the glass-laminate edges were presumably well sealed during exposure. As expected, I_{sc} increased on the average for the borosilicate laminate, but P_{max} decreased by 8 percent. Increased R_s was apparently the cause.

For the soda-lime float, I_{sc} decreased as expected (from the as-cleaned value), and P_{max} decreased from 7 to 10 percent. An increase in R_s caused a portion of the degradation.

The use of Sunadex B led expectedly to an increase in I_{sc}. With Sylgard 184, the decrease in P_{max} was less than 1 percent. The increase in I_{sc} and R_s apparently were offsetting to a substantial degree. With the gel "adhesive", P_{max} decreased 14 percent owing to a large increase in R_s, although it should be noted that only one laminate was fabricated with this combination of materials.

TABLE 42. SUMMARY OF ACCUMULATED CHANGES IN ELECTRICAL CHARACTERISTICS OF GLASS-ENCAPSULATED CELLS WITH LEAD-FOIL EDGE SEALS[a]

Type of Laminate		Accumulative Test Exposures, hr			Accumulated Changes in Electrical Characteristics[f], percent									
					V_{oc}		I_{sc}		P_{max}		R_{sh}		R_s	
Glass[b]	Adhesive	R.H.[c]	UV[d]	T.C.[e]	Δ, %	S.D.	Δ, %	S.D.	Δ, %	S.D.	Δ, %	S.D.	Δ, %	S.D.
Soda-Lime[g] frost	Q3-6527 Gel	384	185	168	−0.93	2.05	−4.10	1.71	−10.2	3.79	−10.0	66.8	62.8	31.4
Borosilicate[h] (7740)	Q3-6527 Gel	384	185	168	−0.17	0.47	0.33	1.25	− 8.3	1.65	15.8	23.9	110	35.0
Sunadex B[i]	Q3-6527 Gel	384	185	168	0.00	--	1.20	--	−14.3	--	2.10	--	136	
Soda-Lime[j] float	Sylgard 184	384	185	168	0.70	0.85	−1.88	0.72	− 6.8	5.07	25.5	24.6	85.6	28.7
Sunadex B[k]	Sylgard 184	384	185	168	0.90	0.33	5.05	0.65	− 0.80	7.29	− 8.95	17.5	127	28.3

(a) Electrical leads sealed with synthetic rubber sealant (1202 T) manufactured by 3M; lead-foil tape was 3M No. 422 which employs an acrylic adhesive.

(b) Glass indicated was used for both the front cover and the back cover (substrate).

(c) 38 C, 97 percent relative humidity.

(d) Xenon lamp, approximately 1 sun.

(e) −40 to 90 C on a 4-hour cycle.

(f) Measurements on as-encapsulated cells found to be in error; therefore, the percentage changes and standard deviations were calculated using the as-cleaned conditions as a base.

(g) Cells 222, 225, and 226.

(h) Cells 201, 203, and 216.

(i) Cell 224.

(j) Cells 298, 299, 303, 305, and 312.

(k) Cells 309, 310, 311, and 315.

CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation indicate that the use of the materials and processes evaluated (without material or process development) probably will not provide an array service life of 20 years. Substantial degradation of power output occurred for all coated and laminated cells. This result must be put in perspective from the points of view of the exposures used and of the cells used.

Two of the artificial exposure environments used were severe: high humidity and temperature cycling. The former generates large effects, especially in increases in series resistance. Clearly, arrays will not experience prolonged continuous exposure to high humidity as in this investigation. Shorter exposures might allow enclosed water to exit the array, decreasing the effect. Just what "accelerating factor" these exposures represent must await a true accelerated test. Temperature cycling from -40 C to 90 C in a 4-hour cycle also represents an accelerating stress. Yet, the cycle extremes are not too different from those temperatures that might be met in some geographic sites. The environment-versus-material difficulties are made manifest in the acrylic laminates. The acrylics possess technical advantages in weatherability, hardness, and optical transmittance. On the other hand, the lack of compliance leads to difficulties in preventing delamination under such temperature cycling. The ultraviolet-radiation exposures used in this investigation were not severe, and do not represent a substantial accelerating stress. Although the polymer laminates were chosen in part to resist UV radiation, the exposures represent but a small fraction of a 20-year life.

The second perspective involves the particular cell used. Many of the degradative effects stem from an increase in series resistance. Undoubtedly, the effects arise from interactions of water vapor with the metallization/silicon interface. Bonds between the silk-screened silver and silicon are known to be more subject to degradation by water vapor than other metallizations, Ti/Pd/Ag for example. Thus, it is expected that the results obtained here represent more nearly a "worst case" than the "best case". This cell metallization was used to reveal effects of environmental exposures in a short period of time and because it is a low cost process that may be used to meet the LSA Project cost goal. Its implications regarding the encapsulation/protection required are noted below.

It should also be kept in mind when assessing these results that, generally speaking, cells are not designed to incorporate encapsulation. Increased short-circuit currents were found in this study for some cover materials, borosilicate glass for example. This effect expectedly arises from increased optical coupling. Moreover, it is clear that the AR coating and the metallization determine in a substantial way what the effects of exposures will be on the cell power output over time. Likely, cheaper encapsulant will be possible to protect a metallization that is less sensitive to water vapor than silk-screened silver.

It should be noted again that the approach in this study was to evaluate presently available materials, without development, for the purpose of defining problems and promising directions for future research and development efforts on encapsulation materials and processes.

With these points in mind, several general conclusions can be drawn from the measured results. Although more evaluation will be required on edge seals and adhesives, glasses are the only materials that demonstratively promise to have a life of 20 years in the environments to be met.(3,7) Borosilicates and so-called iron-free and low-iron glasses have high optical transmittance and result in higher power output than other materials, but are high in cost relative to LSA

Project cost goals. Soda-lime float glass, though lower in cost, penalizes performance through lower optical transmittance in the wavelength range of the cell's most sensitive response. The cost of low-iron glass should decrease with large-volume production and needs to be further examined.

The situation with regard to adhesives to be employed with glass covers is not as clear. To the extent evaluated in this investigation, PVB is the apparent technical choice. Again, it is to be recalled that edge-sealing was not used in certain parts of this investigation. With appropriate edge-sealants, several adhesives might be adequate. Edge-sealing likely will be required because significant degradation in cell output was found in many specimens for all adhesives investigated.

Again excluding the adhesives, several polymer materials show promise as cell top covers insofar as the test results of limited exposure afford. As expected, the halocarbons – "Teflon" FEP for example – would promise adequate weatherability, but they are relatively expensive. Another possible drawback is less-than-ideal optical transmittance. The acrylics likewise, promise adequate weatherability and are less expensive than the halocarbons. Optical transmittance is promising but yellowing occurred in some specimens used in this investigation. The acrylics exhibit a higher surface hardness than some polymerics, an advantage in abrasive environments. On the other hand, the adhesive must be chosen with care; cell breakage can be a problem without adequate stress relief, as was demonstrated in some specimens. Adhesives with polymer materials present a particular problem. They must be chosen for each type of polymer. The silicone adhesives with their low modulus offer distinct advantages in stress-relief functions, but high water permeability is a major disadvantage.

Conformal coatings used alone as encapsulants did not display adequate protection of the cells (with silk-screened silver metallization). This result reflects the measured performance of the two coatings used in this program: a silicone and an acrylic. The caveat mentioned previously regarding development of process parameters must be recalled when assessing these results; the coatings used were thin and there was no assurance that pinhole-free specimens were realized. Further studies of conformal coatings are needed, since they offer the possibility of very low processing costs in automatic array manufacture.

The following summary conclusions and recommendations are made:

(1) Thin conformal coatings of the acrylic and silicone materials investigated do not provide sufficient protection for cells with silk-screened silver metallization. Development efforts on materials and processes should be conducted to utilize this potentially low-cost type of encapsulation.

(2) Acrylic and "Teflon" FEP preformed films promise good weatherability and acceptable optical transmittance. More attention should be given to the selection or development of adhesives that provide adequate bonding and mechanical compliance to mitigate differences in expansion coefficients. Encapsulation designs and processes that minimize the amount of these materials required, and thereby the cost, should be investigated. Multiple-layer films, like the acrylic/polyester film investigated but possibly using other materials, should be the subject of future development.

(3) Borosilicate, low-iron, and soda-lime float glasses represent viable candidate encapsulants for most environments. More work should be performed to develop and evaluate appropriate adhesives, edge seals, and back covers.

(4) An investigation should be made to optimize glass composition for solar-cell encapsulation.

Without further developments in polymers, the single encapsulant with demonstrated weatherability is glass. Presently available glasses with the best properties (borosilicate and iron-free glasses) are too expensive to meet the LSA Project cost goals. Lower cost glasses (soda-lime) exhibit higher optical absorption. As demonstrated in other investigations at Battelle, glass compositions versus glass properties can be handled in a systematic way, taking into account combinations of several finite internal structures of glasses. Currently available computer programs can be modified to direct experimental efforts toward realizing the lowest cost glasses consistent with the best possible technical properties.

(5) Substantial advantages can accrue with regard to system costs and technical performance from integrating the AR coating, metallization, and encapsulation into the cell and array design.

The encapsulation requirements depend heavily on the AR coating and the cell metallization system. Treating each component separately – from the standpoint of technical performance, cost, or ease of fabrication – is not effective. Studies in other programs at Battelle-Columbus demonstrate that optimum choice of material for the AR coating and its thickness depend upon the encapsulant. Other studies have shown that some metallization systems can endure high concentrations of water vapor for relatively long periods, in contrast to the silk-screened silver system. Thus, future encapsulation studies should consider the encapsulant, the AR coating, and the cell metallization as a unit subsystem.

(6) It is recommended that a fundamental study be made of the physical nature of, and the effects of environmental stresses on, the interface region between silicon and silk-screened silver.

Two major points led to this recommendation. First, the silk-screen process is one of the presently known ways to reduce the cost of fabrication of solar cells. The expected cost of this process for cell metallization in automated production is substantially less than the successive vacuum evaporation of a multielement metal system. Second, the susceptibility of cells with silk-screened metallization to environmental stresses is large, as revealed by the experimental results of this investigation. Reduction in the maximum power of encapsulated cells, to be sure, occurred for accountable reasons: e.g., through degradation of the encapsulants or through inadequate initial properties such as low transmittance in specific spectral regions. It is noted, however, that the most prevalent reduction in power must be assigned to the measured increases in series resistance, especially during exposure to high-humidity environments. Additionally, in some cases increases occurred as a result of the encapsulation process itself, that is, without prolonged environmental exposure. Within the scope of this investigation, it was possible to diagnose the physical changes occurring in the cell only through changes in the electrical characteristics. It is postulated that the series-resistance effects result either from changes in the conductivity of the metallization or from changes in the bonding layer between the metallization and silicon, or both. Accordingly, if the screen-printing process is to figure prominantly as a low-cost step in the fabrication of silicon solar cells, the physical changes in the interface region must be better understood so as to lead to improved series-resistance response as well as to low-cost encapsulation systems.

C-2

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ADDENDUM

MINIMODULES FOR DEMONSTRATION OF ENCAPSULATION WITH POLYMER CONFORMAL COATINGS AND FILM LAMINATION

Purpose

For the ninth LSA Project Integration Meeting (PIM), held in April, 1978, Battelle was requested to prepare and submit to JPL several minimodules that would serve to demonstrate low-cost encapsulation concepts. The purposes of these constructions are:

- To initiate development of potentially low-cost high-performance encapsulation system designs and concepts for terrestrial photovoltaic devices.
- To illustrate these designs and concepts through the construction of models.
- To develop some preliminary test data on the cost and performance of these models. (The minimodules were fabricated *without* any preceding materials and process development and without any attempt at optimizing the design.)
- To provide information and a basis for recommendations for materials and process-development efforts to be conducted in the future in the encapsulation area.

Battelle prepared designs for this task that illustrate two basic concepts for module encapsulation, as described subsequently.

Background

There are no currently known encapsulation systems that will meet both the cost and performance goals of the LSA project. There is, then, a need to develop materials and encapsulation systems having the potential of achieving these goals and to characterize the stability and lifetime of these systems under appropriate environmental stress conditions.

The nature of the specific physical, chemical, and other requirements imposed on encapsulation systems are highly dependent on the specific materials and processes used in fabricating the other parts of the module (e.g., cell metallization, AR coating, interconnects, etc.). The allowed cost, within the goals of the LSA project, for encapsulation materials and structures must then reflect the needs of the specific cell/module technology that it is intended to protect. As an example, some of the fabrication technologies that utilize low-cost processes, such as thick-film metallization techniques, may require a higher degree of exclusion of water or other atmospheric constituents than the higher-cost technologies. Encapsulation costs for modules based on these low-cost technologies will probably be necessarily higher than those for other technologies. Uncertainties in the ultimate low-cost cell technology make it difficult to accurately specify the protective requirements for mid- and long-term terrestrial modules. At present it is necessary to identify low-cost materials, processes, and systems that can be adapted or modified to provide adequate protection without significantly impacting their cost, and/or to identify materials, processes, and systems that provide adequate protection and seek ways to lower their cost without significantly impacting performance.

Selection of Concepts/Designs

The minimodule concepts chosen for this demonstration were

(1) Substrate-mounted cells with a polymer conformal coating

(2) A polymeric film laminate structure.

A design with a glass cover using a polymer layer for adhesion to the cells was also recommended, but minimodules of this general type were being prepared by other contractors for this demonstration effort.

The conformal coating approach is potentially one of the lowest cost concepts because of the simplicity of the design and the low cost of the fabrication/application process in mass production. The conformal coating material used to illustrate the concept was Eccocoat AC-8 acrylic. This material was selected on the basis of previous experience in working with it as part of the evaluation of encapsulation materials described in the body of the report, although it has been found that this acrylic coating does not provide adequate protection for cells with moisture-sensitive contacts. The substrate is a critical cost factor in this design. Three types of substrate materials were evaluated as part of this demonstration effort:

(1) A fiberglass-impregnated polyester sheet (GPO-1 board)

(2) A bead-type Styrofoam, painted with a titanium dioxide-impregnated acrylic

(3) A bead-type styrene/acrylonitrile, painted with a titanium dioxide-impregnated acrylic.

The paint used on the latter two substrate materials provides protection against ultraviolet radiation. The basic design of the conformally coated module concept is illustrated in Figure A-1. The adhesive used to bond the cells to the substrates was Scotch-Weld 2216 epoxy; again, this choice was based on availability and experience in working with the material and also the short time allowed for construction and delivery of the minimodules. Lower-cost adhesives with acceptable properties do exist.

The polymeric film laminate structure used is illustrated in Figure A-2. At the present state of the art, several candidates (i.e. material combinations) in this category can provide greater protection against water-vapor penetration, particularly if edge sealing is incorporated, than the conformal coating; however, the cost, including both materials and fabrication cost, is generally higher. The concept can be adapted to installation on an existing roof or other structure, thereby eliminating the need for incorporation of a rigid substrate in the design. The polymer film material used in the minimodules prepared to demonstrate this concept was Flexigard, a 3M-manufactured composite material. The adhesive used was Silgrip SR-573 silicone. The Flexigard film was 0.005 inch thick and apparently consists of a layer of acrylic and a layer of polyester material, although this information was not provided by the manufacturer.

Minimodule Construction

The materials, materials preparation steps, and fabrication processes and procedures used in preparing the minimodules were selected on the basis of past experience in fabricating single-cell evaluation samples and the availability of materials. The fabrication was implemented with essentially no effort at process and materials development because of the level of effort and short time allowed for fabrication and delivery. As a consequence, the minimodules supplied represent the concepts but do not represent an optimized structure in terms of materials thicknesses used, application techniques, curing times and temperatures, etc.

The photovoltaic cells used in these minimodules were 3-inch-diameter silicon cells, 0.012 inch thick, with evaporated Ti/Pd/Ag metallization. They were manufactured by OCLI. As requested by JPL, each module contained nine cells, in three strings of three cells each. One group of cells had been assembled into strings of three cells each prior to delivery to Battelle. The interconnects used in fabricating these strings were 0.002-inch-thick Kovar or beryllium copper with out-of-plane stress-relief loops having a maximum height of 0.025 inch. This type of string, because of the height irregularities, was found to be incompatible with the film lamination process and was used primarily in the fabrication of the conformally coated minimodules. For the film laminate concept, individual cells were obtained and fabricated into three-cell strings at Battelle using copper-ribbon interconnects incorporating in-plane stress-relief loops.

On the conformally coated minimodules, a coating of approximately 0.005 inch of the Eccocoat AC-8 acrylic was used. This coating was applied by brush in this effort and was cured at low temperature to minimize bubbling. The adhesive, Scotch-Weld 2216 B/A, was also applied by brush, to a thickness of approximately 0.010 inch. The thickness of the fiberglass-filled polyester board (GPO-1), used as one of the substrate materials for this concept, was approximately 1/16 inch, while the bead-type Styrofoam and the bead-type styrene/acrylonitrile substrates were each 1 inch thick. All substrates were recessed for ease of cell positioning. The expanded bead-type substrate was preshrunk at an elevated temperature (approximately 90 C) to enhance thermal stability. Of the two low-cost bead-type substrates used, the styrene/acrylonitrile exhibited the better thermal stability.

The fabrication procedure for construction of the conformally coated minimodules was as follows:

- Thermally preshrunk the substrate material (in the case of the bead-type substrates)
- Sized substrates and produced recesses for cell positioning
- Applied paint to bead-type substrates
- Applied adhesive and installed cell strings
- Applied conformal coating and cured.

Figure A-3 shows a completed conformally coated minimodule, consisting of three electrically independent three-cell strings mounted on the GPO-1-type substrate. A similar type of minimodule with the bead-type styrene substrate is shown in Figure A-4.

Materials cost (excepting cell costs) estimates for the conformally coated minimodules are as follows (units are dollars per square foot).

(1)	Eccocoat AC-8, 0.005 in.	0.08
	Scotch-Weld 2216 B/A, 0.003 in.	0.28
	GPO-1 Substrate, 1/16 in.	0.71
		1.07

(2)	Eccocoat AC-8, 0.005 in.	0.08
	Paint (R & H Rhoplex E-269 with Du Pont R-942 pigmented slurry)	0.03
	Scotch-Weld 2216 B/A, 0.003 in.	0.28
	Bead-type styrene board, 1 in.	0.15
		0.54

There is a clear need for cost reduction here, and the most costly items are the adhesive and the GPO-1 substrate. The bead-type Styrofoam board is estimated to be approximately \$0.04/ft^2 cheaper than the expanded bead styrene/acrylonitrile, but has a lower thermal stability. The thickness required has not been determined. Other low-cost substrates can also be considered, such as painted metal sheet or wood products, although it should be noted that neither these nor the styrene material have been shown to be suitable in performance. It should be possible to reduce adhesive costs to a figure lower than the above by using a lower cost material. Note that a more practical thickness of 0.003 inch was used in the adhesive cost estimate, rather than the thicker layer employed in this effort. Also, lower costs may be realized depending on projections of quantity buying.

The film laminate minimodules used two layers of 0.005 inch-thick Flexigard and 0.010 – 0.015 inch of Silgrip SR-573 adhesive. The available lamination equipment was not suitable for laminating areas as large as that represented by the three-string (nine-cell) minimodule (1 ft^2), so each three-cell string was encapsulated separately, and then three of these encapsulated strings were adhesively attached to yield the nine-cell minimodule. Figure A-5 shows a version of the laminate structure in which an attempt was made to laminate three strings at once.

The materials cost estimate for the laminate structure is as follows (costs in dollars per square foot):

(3)	Flexigard film (2 layers), 0.005 in. each side	0.50
	Silgrip SR-573, 0.003 in.	0.18
		0.68

If an expanded bead styrene board substrate or other less expensive material is used in place of one of the Flexigard films, total materials costs would be reduced to \$0.58/ft^2. It is noted that the cost of this dual-layer film in future high production quantities is particularly difficult to project.

Testing and Test Results

Full characterization of the electrical properties at Battelle was not possible within the allowed time frame. The open-circuit voltage of each three-cell string was measured under arbitrary but consistent illumination conditions ($\sim$ 1 sun) to ensure continuity. These open-circuit voltages ranged from 1.63 to 1.73 volts, with a mean of 1.68 volts and a standard deviation of 0.03. Representative data (100 mw/cm^2 illumination) on individual cells were also taken. Data from a representative unencapsulated cell are given below.

V_{oc} – 0.588 volt
I_{sc} – 1204 milliamperes
Fill Factor – 0.73
Efficiency – 11.64 percent
R_s – 0.61 ohm
R_{sh} – 1400 ohms

The modules were flashed tested by JPL upon delivery and after temperature cycling and humidity testing for selected modules. Some of the data from the as-received measurements are given in Table A-1.

Results of measurements made on selected modules after temperature cycling at JPL are given in Table A-2. The data given are for conformally coated modules. One of the film laminate modules was also subjected to thermal-cycle stressing. However, this module was inadvertently removed from its support mount before the test and, since it was not intended to be self-supporting, it collapsed during the test. This resulted in fracturing of the cells. Consequently, no data were obtained on the film laminate structure after thermal cycling.

Most of the strings tested showed minimal changes as a result of the test (1 to 3 percent). Module 7 had two strings which showed relatively large changes. The reasons for this are not known at this time.

Measured efficiencies for the same modules after exposure to high humidity stress in addition to the thermal cycling are given in Table A-3. The change in efficiency is relative to the as-received value. Again, the changes are small with a few anomalous exceptions. Several strings show slight improvement as compared with their performance after thermal cycling alone. This is probably due to variability in the measurement technique.

Conclusions from Minimodule Fabrication

The models fabricated illustrate two viable, general approaches to low-cost, high-performance encapsulation systems. Developmental work is obviously needed to provide materials and processes which enable both of these criteria to be met in the same structure.

Materials costs for the film laminate model fabricated are less than the 1982-goal allotment of \$11/m^2; however, considerable development and modification are necessary to achieve the 1986-goal allotment of \$3/m^2. The fabrication costs (other than materials) for the structure have not been assessed, since analysis of a large-scale production concept was not within the scope of the present effort. With appropriate films and possibly incorporation of edge sealing, the film laminate concept may, however, provide adequate protection for most of the metallization systems being considered. Development work should emphasize selection/modification of materials for the multiple-layered film concept and development of fabrication techniques.

The estimated materials costs for the lowest cost conformal coating models (i.e., those using the bead-type polymer substrates) also are less than the 1982-goal allotment, and with some of the modifications described, they could begin to approach the 1986-goal allotment. Performance is a major question with this structure. Present low-cost materials suitable for this concept appear not to provide adequate protection for modules incorporating cell metallization and interconnect systems which are moisture sensitive, such as the screen-printed silver metallization. These materials may, however, provide adequate protection for moisture-resistant metallization and interconnect systems. Development work should emphasize materials with improved capability for excluding water vapor and application processes which yield coatings with high integrity.

Other conclusions resulting from this effort are that encapsulation system design and cost need to be treated in the context of the needs of specific types of cells and modules, and that encapsulation system design should be treated as an integral part of cell and module design (metallization, antireflective coating, etc.) in order to realize maximum performance and minimum cost.

TABLE A-1. FLASH-ILLUMINATION MEASUREMENTS OF ELECTRICAL CHARACTERISTICS OF AS-RECEIVED MODULES (PERFORMED AT JPL)

Module Type	Module Number	String Number	V_{oc}, volts	I_{sc}, amperes	Fill Factor	Efficiency, percent
Film Laminate	1	A	1.82	1.13	0.72	10.8
		B	1.83	1.12	0.73	10.8
		C	1.82	1.13	0.71	10.8
Film Laminate	2	A	1.83	1.19	0.72	10.8
		B	1.83	1.27	0.72	10.9
		C	1.82	1.28	0.72	10.7
Film Laminate	3	A	1.84	1.12	0.73	10.9
		B	1.84	1.14	0.68	10.2
		C	1.84	1.15	0.71	11.0
Film Laminate	4	A	1.83	1.13	0.62	9.4
		B	1.75	1.11	0.68	9.7
		C	1.76	1.09	0.73	10.2
Film Laminate	5	A	1.81	1.08	0.65	9.2
		B	1.83	1.16	0.69	10.7
		C	1.77	1.11	0.72	10.3
Conformal Coating, GPO-1 Substrate	6	A	1.82	1.14	0.70	10.6
		B	1.81	1.09	0.74	10.6
		C	1.81	1.12	0.73	10.7
Conformal Coating, GPO-1 Substrate	7	A	1.80	1.13	0.70	10.1
		B	1.78	1.11	–	10.6
		C	1.76	1.11	0.73	10.4
Conformal Coating, GPO-1 Substrate	8	A	1.76	1.10	0.75	10.7
		B	1.77	1.11	0.73	10.4
		C	1.81	1.10	0.74	10.7
Conformal Coating, Styrofoam Substrate	9	A	1.82	1.15	0.72	10.9
		B	1.83	1.16	0.71	11.0
		C	1.81	1.17	0.72	11.1
Conformal Coating, Styrene/Acrylonitrile Substrate	10	A	1.84	1.15	0.71	11.0
		B	1.84	1.14	0.71	10.8
		C	1.85	1.16	0.71	11.2

TABLE A-2. EFFICIENCY MEASUREMENTS ON THERMALLY CYCLED MODULES (JPL FLASH-ILLUMINATION MEASUREMENTS)

Module Number	String Number	Efficiency After Thermal Cycling, percent	Change in Efficiency due to Thermal Cycling, percent
7	A	8.8	-12.9
	B	7.7	-27.3
	C	10.3	- 1.0
8	A	10.2	- 4.7
	B	10.2	- 1.9
	C	10.4	- 2.8
9	A	10.7	- 1.8
	B	10.8	- 1.8
	C	10.8	- 2.7
10	A	10.7	- 2.7
	B	10.6	- 1.8
	C	11.0	- 1.8

TABLE A-3. EFFICIENCY MEASUREMENTS ON MODULES AFTER EXPOSURE TO THERMAL-CYCLING AND HIGH-HUMIDITY ENVIRONMENTS (JPL FLASH-ILLUMINATION MEASUREMENTS)

Module Number	String Number	Efficiency After Exposures, percent	Change in Efficiency due to Exposures, percent
7	A	9.4	- 6.9
	B	8.8	-17.0
	C	10.4	0.0
8	A	10.6	- 1.0
	B	10.6	+ 1.9
	C	10.7	0.0
9	A	10.8	- 1.0
	B	9.8	-10.9
	C	11.0	- 1.0
10	A	11.0	0.0
	B	10.6	- 1.8
	C	9.9	-11.6

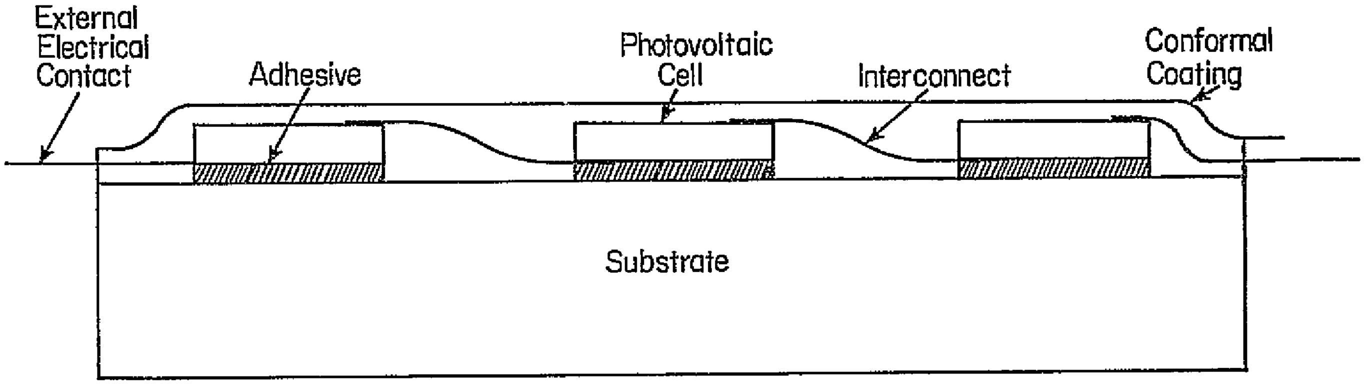

FIGURE A-1. CONFORMALLY COATED MODULE

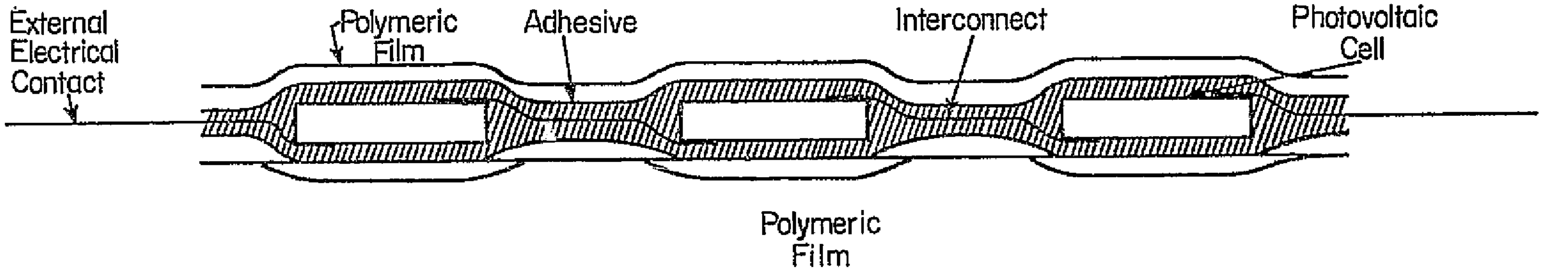

FIGURE A-2. FILM LAMINATE MODULE

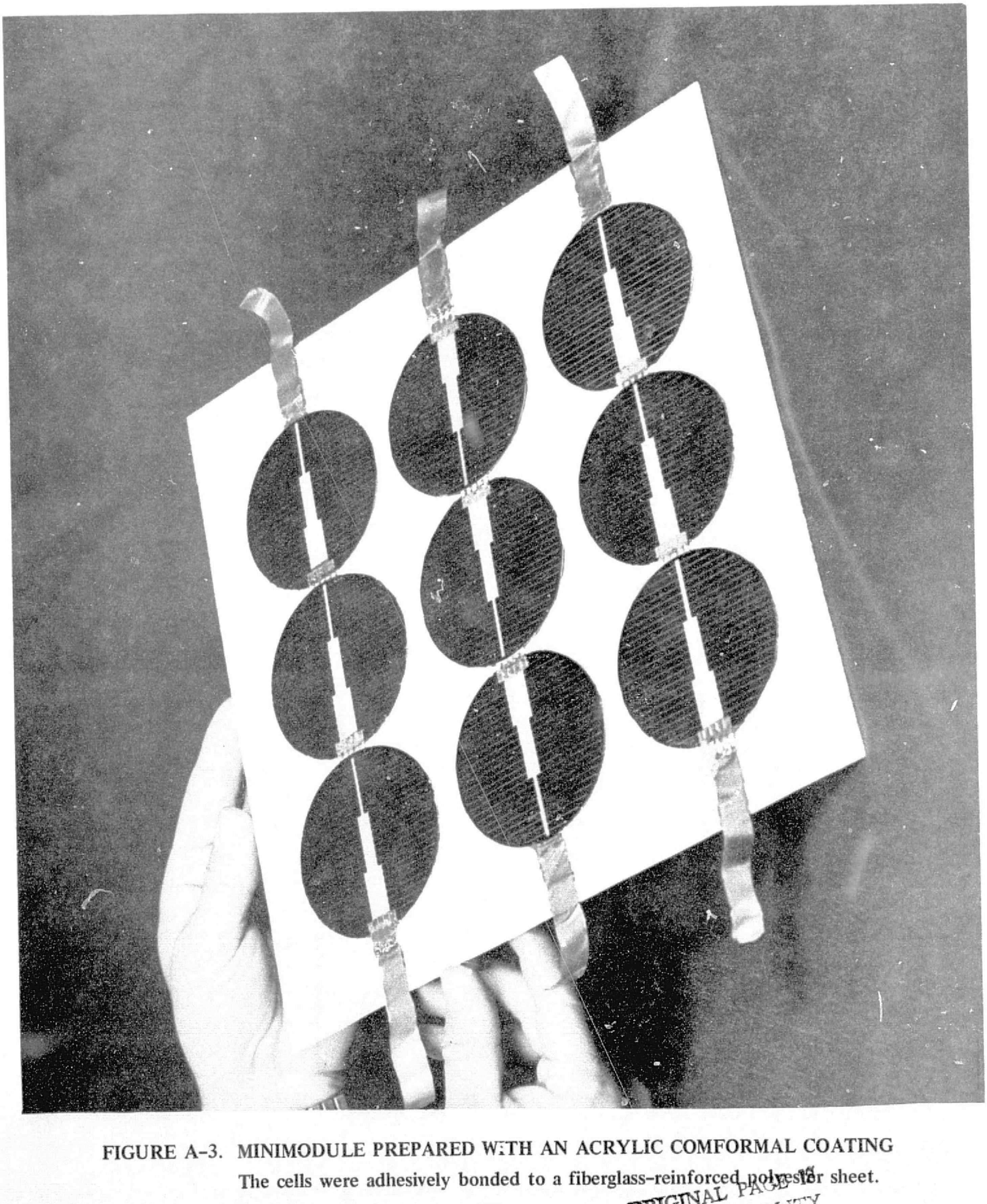

FIGURE A-3. MINIMODULE PREPARED WITH AN ACRYLIC COMFORMAL COATING

The cells were adhesively bonded to a fiberglass-reinforced polyester sheet.

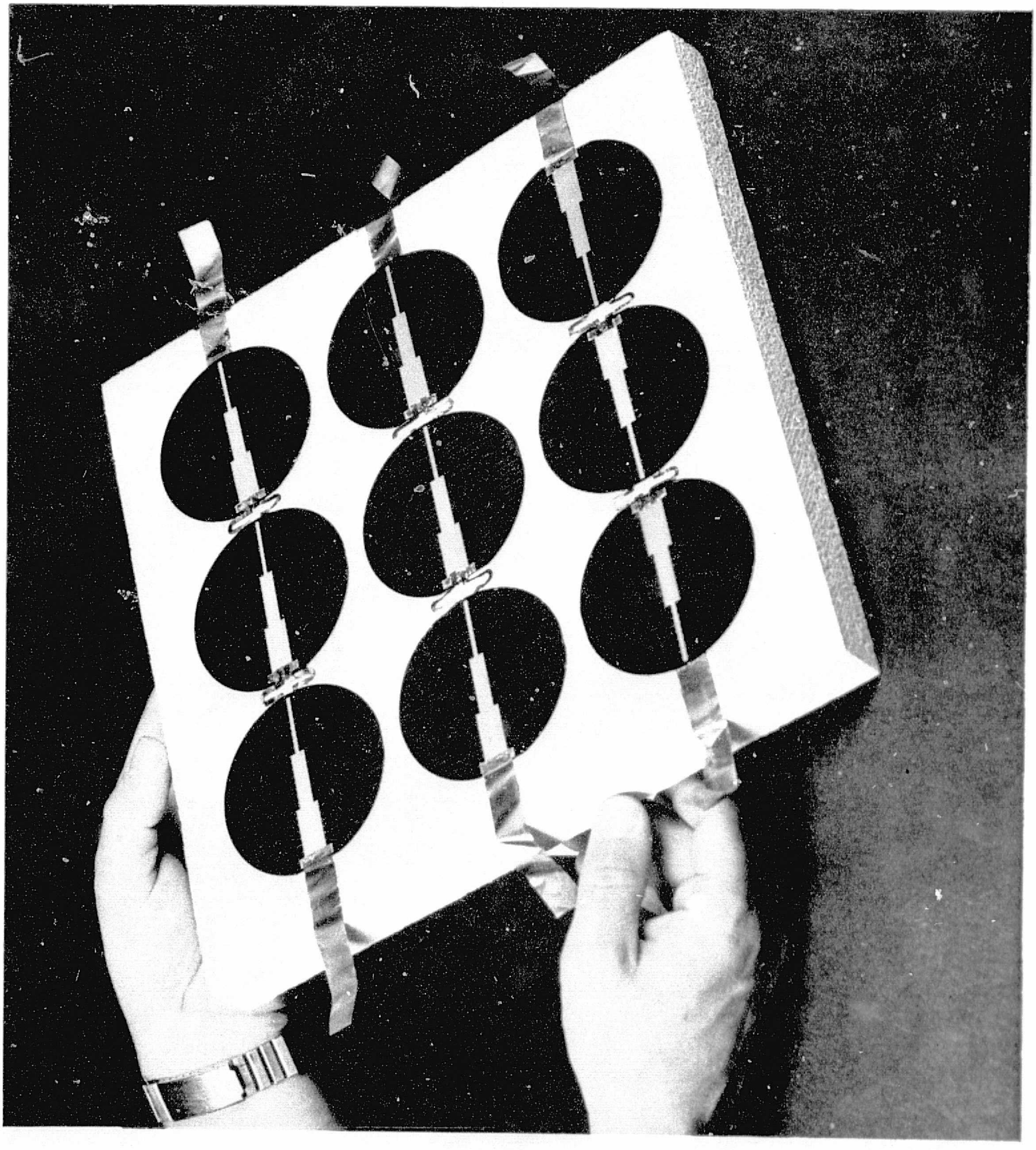

FIGURE A-4. MINIMODULE PREPARED WITH AN ACRYLIC CONFORMAL COATING

The cells were adhesively bonded to a bead-type Styrofoam. Coating was 0.005 inch thick.

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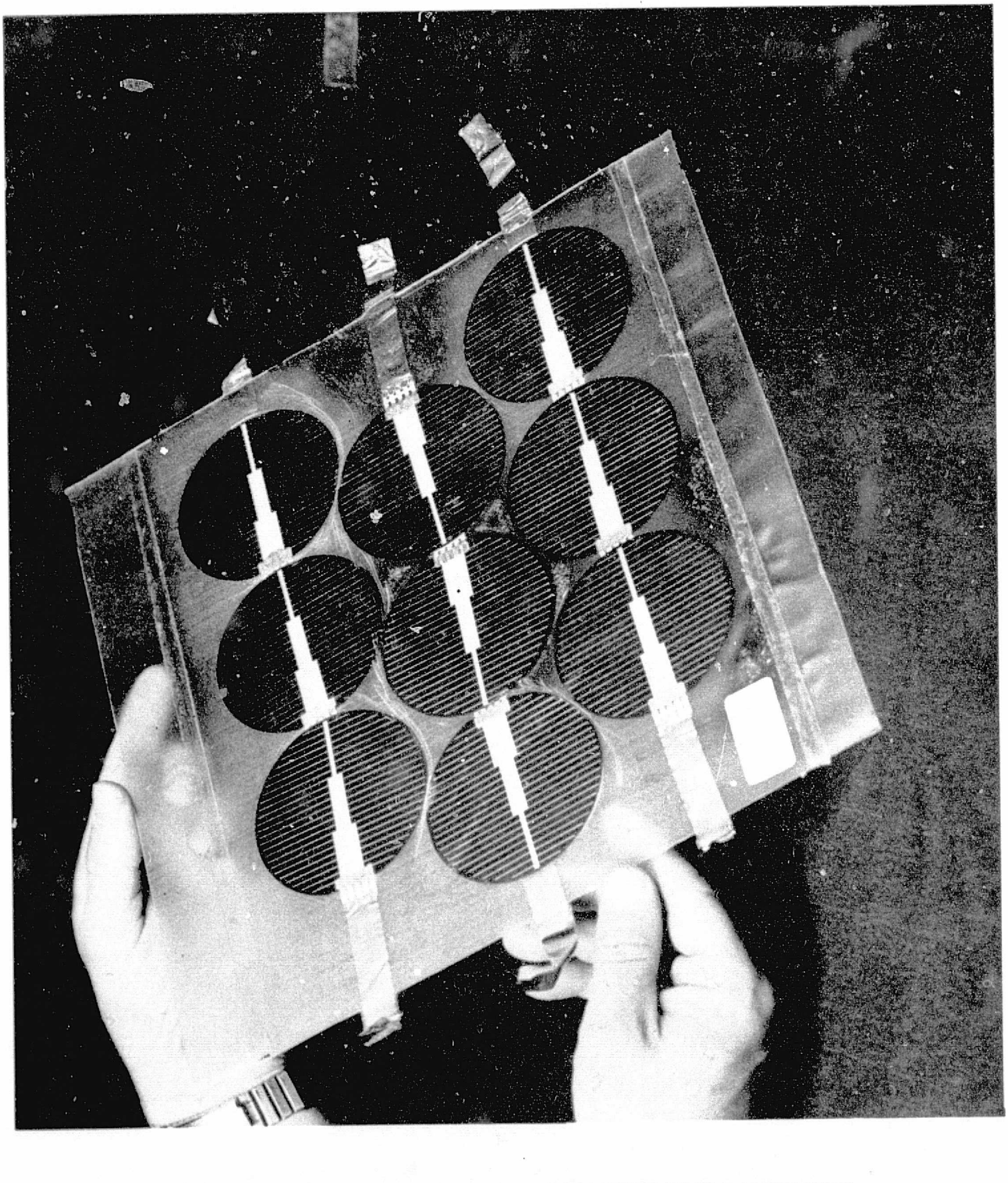

FIGURE A-5. MINIMODULE PREPARED BY POLYMER FILM LAMINATION
The film material was 0.005-inch thick Flexigard, and silicone adhesive was used in the lamination.