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INVESTIGATION OF TEST METHODS, MATERIAL PROPERTIES, AND PROCESSES FOR SOLAR CELL ENCAPSULANTS

EIGHTH ANNUAL REPORT

1984

JPL Contract 954527
Project 6072.1

For

JET PROPULSION LABORATORY
4800 Oak Grove Drive
Pasadena, California 91103

ENCAPSULATION TASK OF THE LOW-COST
SILICON 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.

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I. SUMMARY

Springborn Laboratories, Inc. is engaged in a study of potentially useful low cost encapsulation materials for the Flat-Plate Solar Array Program (FSA) funded by the Department of Energy and administered by the Jet Propulsion Laboratory. The goal of the program is to identify, test, evaluate and recommend encapsulation materials and processes for the fabrication of cost-effective and long life solar modules.

The pottant holds a central role in encapsulation systems due to its position in direct contact with the solar cell. It must have the properties of transparency, low modulus, low melting point, low cost and must also be useable in some type of high speed manufacturing process for the production of modules. In addition, the pottant must provide reliable protection to the cells for a service life of thirty years. Over the past few years Springborn Laboratories has developed a pottant based on ethylene-vinyl acetate copolymer, now generally known as "EVA". This material appears to offer the best combination of processability , performance and low cost,and has received wide commercial acceptance. Due to the strong interest in EVA, it was decided to publish the history of its development, which is the subject of Section III of this report. The evolution of EVA pottant is discussed in terms of its functional requirements, resin selection, stabilization, compounding, manufacturing use and environmental aging properties. This discussion will, hopefully, add to the understanding of this successful new potting compound.

A program of accelerated aging is being conducted for the purpose of (a) generating empirical and practical data relating to longevity ,(b) rating and ranking of the stability of candidate formulations, and (c) generating data that may be used in mathematical models for the prediction of service life.

Although a variety of aging methods are being used for this work, the use of Outdoor Photo Thermal Aging Reactors (OPTAR) appears to be the most promising. These devices age polymers in natural sunlight while accelerating the degradation reactions with heat. They are on only during the sunlight hours and are currently operated at 70°, 90° and 105°C. The OPTAR technique appears to be the most useful yet discovered for assessing the relative aging performance of

encapsulation materials in reasonably short periods of time. Some candidate pottants may be degraded in as little as 2,000 hours (@ 105°C), and advanced formulations have been discovered that extend this mean time to failure. Comparative aging studies have successfully identified a new oligomeric hindered amine light stabilizer (HALS) (Cyasorb UV-3346, American Cyanamide) as having potential for further extending the service life of present EVA compounds.

The OPTAR method was initially intended for use in the evaluation of whole modules. Modules containing four pottant formulations have been under exposure for 5,000 hours and examination indicates that the most destructive effect at any temperature is the presence of metallic copper. Apart from this effect, no changes are observable in the modules exposed at 70°C. At 90°C, the two EVA formulations cured with Lupersol-101 peroxide show signs of discoloration and slight corrosion of the metallic components are also apparent. All the modules are in generally good condition. At the 105°C exposure the signs of degradation are more obvious. The presence of copper has a violent degradation reaction, however it does not spread far from the location of the metal. All the pottants tend to discolor at this temperature. The effect is pronounced in the EVAs cured with Lupersol 101, but slight in the pottants cured with Lupersol-TBEC. Other observable changes are slight corrosion of the interconnects and breakage of the glass outer covers due to thermal shock. The power generating ability of all the modules seems to be unimpaired. These experiments definitely demonstrate the improvement in performance that occurs when all the encapsulation components are combined to mutually protect each other. Finally, lifetime modelling experiments performed with the OPTAR devices appear to be extremely encouraging. Using unstabilized polypropylene as a model compound, a linear relationship (Arrhenius) was found when the induction period, log t_i, was plotted as a function of absolute temperature. If this relationship can be found for pottant formulations, then reasonable predictions of real time service life may become possible.

Substrates are proportionally the highest costing construction element required in the PV module. Of the $18 (1984 $) per square meter allocated for the encapsulation components, approximately 50% of the cost, ($9/m^2), may be taken by the load bearing component. Wood products, such as hardboard, are potentionally the lowest cost candidate substrates identified to date. The high modulus (0.5 to 1.0 x 10^6 psi) and low cost (approximately \$0.14/ft^2) satisfy the cost and load deflection requirements. The difficulty with the use of these materials lies in the very high hygroscopic expansion coefficients.

The cost of a wood product based substrate must, therefore, include raw material costs, plus the cost of additional processing to impart hygroscopic inertness. This protection is thought possible by a two step, or "split" process, in which a flexible laminate containing the cell string is prepared; first in a vacuum process and then adhesively attached with a back cover film to the hardboard in a subsequent step. The additional processing cost is calculated to be \$3.19 per square meter (1984 \$). This additional cost component may be acceptable if an expensive load bearing material, such as glass, is replaced with a wood product. Overall module manufacturing costs could possibly be reduced by several dollars per square meter in large volume operations. The cost calculations and product flow charts for this process are detailed in the appendix.

An experimental program is continuing to determine the usefulness of soil resistant coatings. These coatings are intended to be surface treatments applied to the sunlight side of solar modules and function to prevent the persistent adhesion of soil to the surface, aid in its removal, and consequently keep the power output high. These treatments have been applied to "Sunadex" glsss, "Tedlar" polyvinyl fluoride film and "Acrylar" oriented acrylic film. The treatments are based on fluorosilane chemistries. After thirty-eight months of outdoor exposure, a fluoro treatment designated E-3820, was found to be the best coating for all three outer surfaces and result in significantly better soil resistance than the controls. This material still appears to be active after three years, whereas the other candidates have all lost their effectiveness. Based on standard solar cell measurements, the improvement in power output using this treatment is estimated to be about 1% for Sunadex glass, 3.8% for Tedlar and 3.2% for Acrylar. These treatments may provide a passive and cost effective way to maintain high power for PV arrays in the field.

II. INTRODUCTION

Photovoltaic modules consist of a string of electrically interconnected silicon solar cells capable of producing practical quantities of electrical power when exposed to sunlight.

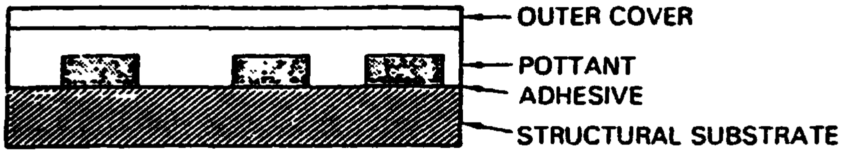
To insure high reliability and long-term performance, the functional components of the solar cell module must be adequately protected from the environment by some encapsulation technique. The potentially harmful elements to module functioning include moisture, ultraviolet radiation, heat build-up, thermal excursions, dust, hail, and atmospheric pollutants. Additionally, the encapsulation system must provide mechanical support for the cells and corrosion protection for the electrical components. The encapsulation system is defined as all the construction materials required in a module to provide this mechanical support and environmental isolation. In addition, the module must be based on construction materials and design considerations that meet the field operating requirements while also maximizing the cost performance. This is the goal of this program; to identify and develop encapsulation systems consistent with the PV module operating requirements of 30 year life and a target cost of \$0.70 per peak watt (\$70/m^2) (1980 dollars)(a) . Assuming a module efficiency of ten percent, which is equivalent to a power output of 100 watts per m^2 in mid-day sunlight, the capital cost of the modules may be calculated to be \$70.00 per m^2. Out of this cost goal, only 20 percent is available for encapsulation due to the high cost of the cells, interconnects, and other related components. The encapsulation cost allocation may then be stated as \$14.00 per m^2 which included all coatings, pottant and mechanical supports for the cells.

Assuming the flat-plate collector to be the most efficient design, photovoltaic modules are considered to be of two basic types, substrate and superstrate, and to be composed of seven basic construction elements. The design types are diagramed as follows:

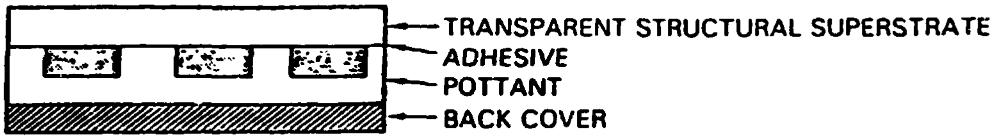
(a) JPL Document 5101-68
The former cost allocation for encapsulation materials, was \$2.50/m^2 (0.25/ft^2) in 1975 dollars, or \$3.50/m^2 (\$0.35/ft^2) in 1980 dollars. The current cost allocation of \$14/m^2 is an aggregate allocation for all encapsulation materials including an edge seal and gasket.

BASIC MODULE TYPES

SUBSTRATE-BONDED



SUPERSTRATE-BONDED



The seven basic construction elements are : (a) outer covers, (b) transparent superstrates, (c) pottants, (d) substrates, (e) back covers, (f) gaskets and edge sealing, and (g) adhesives of primers.

Throughout this program, extensive surveys have been conducted into many classes of materials in order to identify and compound or class of compounds optimum for use as each construction element.

The results of these surveys have also been useful in generating first-cut cost allocations for each construction element, which are estimated to be as follows (1980 dollars):

Construction Elements	Approximate Cost Allocation* ($\$/m^2$)
Substrate/Superstrate (Load Bearing Component)	$ 7.00
Pottant	1.75
Primer	0.50
Outer Cover	1.50
Back Cover	1.50
Edge Seal & Gasket	1.85

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* Allocation for combination of construction elements: $\$14/m^2$.

From the previous work, it became possible to identify a small number of materials which had the highest potential as candidate low cost encapsulation materials.

In addition to materials, two fabrication processes have been explored: vacuum bag lamination and liquid casting. In vacuum bag lamination the pottant is handled as a dry film of formulated polymer that is used to sandwich the cell string. Encapsulation is completed by the application of vacuum and heat. In the casting process the pottant is handled as a high viscosity liquid that is pumped around the cell string. Curing to a rubbery solid is then accomplished by the application of heat.

Recent efforts have emphasized the identification and development of potting compounds. Pottants are materials which provide a number of functions, but primarily serve as a buffer between the cell and the surrounding environment. The pottant must provide a mechanical or impact barrier around the cell to prevent breakage, must provide a barrier to water which would degrade the elctrical output, must serve as a barrier to conditions that cause corrosion of the cell metallization and interconnect structure, and must serve as a barrier to conditions that cause corrosion of the cell metallization and interconnect structure, and must serve as an optical coupling medium to provide a maximum light transmission to the cell surface and optimize power output. Due to its central role in the encapsulation scheme, the pottant has received more emphasis than any other construction element. In the past few years this has lead to the development and commerciallization of "EVA" as a long life low cost pottant available in sheet form for vacuum lamination processing.

This report presents the following topics:

(1) The historical development of EVA; including the functional requirements, polymer selection, curing, stabilization, production and module processing.

(2) Acclerated aging; this section details the construction and use of a new method for the accelerated aging of polymers. This method more closely resembles the conditions that may be encountered in actual module field exposure and additionally may permit service life to be predicted accurately.

(3) Hardboard analysis; this section completes the studies on the use of hardboard as a low cost candidate substrate material.

(4) Anti-soiling treatments; this is an update on the performance of surface treatments useful for imparting a self-cleaning property to modules.

III. EVA - HISTORICAL DEVELOPMENT

Silicon solar cell modules are under continuous development and commerciallization as a alternate source of electrical power. The cells themselves should be capable of indefinitely long service life, however, they are extremely fragile and prone to breakage. In order to insure high reliability and long term performance, the cells must be adequately protected by some type of encapsulation, and the encapsulation itself must be environmentally stable. The potentially harmful elements to module functioning include moisture, ultraviolet radiation, heat build-up, thermal excursions, dust, hail, and atmospheric pollutants. Additionally, the encapsulation system must provide mechanical support for the cells and corrosion protection for the electrical components.

These protective functions may be met by an appropriately designed module that incorporates materials and construction elements that meet these needs. The pottant is the component that is directly in contact with the solar cells and therefore holds a central role in the encapsulation.

The fragile cells require three basic forms of protection, (a) mechanical support and fracture protection, (b) electrical isolation and (c) environmental isolation and the prevention of corrosion. In addition, the pottant serves as a transparent medium that helps to optically couple the cell and enhance its use of sunlight for power generation.

A. Functional Requirements

From the basic needs required for cell protection, a list of requirements for pottant performance evolved. Considering cost, processing and material characteristics polymers was selected as the most logical materials class for this function. A list of required properties was then created in order to assist materials selection. These initial properties are given as follows:

Pottant Specifications

	Characteristic	Specification
1.	Glass transition temperature (T_g)	<- 40°C
2.	Total hemispherical light transmission through a 20-mil-thick film integrated over the wavelength range from 0.4 μm to 1.1 μm	> 90% of incident
3.	Hydrolysis	None at 80°C , 100% RH
4.	Resistance to thermal oxidation	Stable up to 85°C
5.	Mechanical creep	None at 90°C
6.	Tensile modulus as measured by initial slope of stress-strain curve	< 3000 lb/in.^{2} at 25°C
7.	Fabrication temperature	<170°C for either lamination or liquid pottant systems
8.	Fabrication pressure for lamination pottants	$\leq$ 1 atm
9.	Chemical inertness	No reaction with embedded copper coupons at 90°C
10.	UV absorption degradation	None at wavelength >0.35 μm
11.	Hazing or clouding	None at 80°C, 100% RH
12.	Minimum thickness on either side of solar cells in fabricated modules	6 mils
13.	Odor, human hazards (toxicity)	None
14.	Dielectric strength	Sufficient to electrically isolate the cells and interconnects
15.	Process compatability	Compatible with automated cell handling and encapsulation equipment
16.	Cost	As low as possible

Many of these requirements can be met by polymeric materials, however, trade-offs between properties such as cost, processing temperature and environmental stability had to be examined for the selection of suitable candidates.

Without protection from ultraviolet, the classes of candidate potting materials are limited to fluorocarbons, silicones, and acrylics.[a] The first two are extremely expensive and, in the case of fluorocarbons, entirely unprocessable without prohibitively high temperatures.

The silicone rubbers have excellent processing characteristics, being pourable and cureable at room temperature, but the cost of $6 - 9/lb excluded them from consideration. The many acrylic compounds available have desirable low prices , but no commercial products exist in an elastomeric or usable form from directly encapsulating cells.

An alternative to the use of these inherently weatherable materials was the idea of coatings. The possibility of developing weatherable and UV screening protective films and coatings may permit a much broader range of polymers to be considered for potting applications. It may be possible to use a cost-effective, but otherwise unweatherable, polymer successfully as a pottant provided that sufficient external protection is supplied.

B. Polymer Selection

Candidate polymer selection proceeded through three considerations: (a) select a commercial material that meets the specifications. If no such material can be identified, then, (b) select a commercial material and chemically modify it so that it meets the specifications. If no commercial materials exist that can be suitably modified, then (c) synthesize a polymer with the required properties.

Extensive surveys were done to identify potential candidate materials and all commercially available transparent polymers were identified and tabulated in four price ranges.(1) The tables also included information of processability, physical properties, cost, and a prognosis for stabilization.

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[a] Poly(methyl methacrylate) only. Commercial: Plexiglas, Lucite

The polymers surveyed encompassed a great variation in physical properties and chemistry and included such materials as the following: polyvinyl chloride, polystyrene, polyethylene, polyesters, ionomer, polyamides, cellulosics, urethanes, silicones, etc. Due to the need for a compliant low modulus compound, transparent elastomers were surveyed. A partial list follows:

Transparent Elastomers

Elastomers	Considerations
Ethylene/Ethyl Acrylate	High Melt Viscosity
Plasticized PVC	Thermoplastic
Ethylene /Propylene/Diene	Not Weatherable
Ethylene/Propylene	Not Weatherable
Styrene/Butadiene	Not Weatherable
Ionomer	Process Temperature High
Polyvinyl Alcohol	Water Soluble
Thermoplastic Urethane	High Cost
"Viton" Polymers	Very High Cost
Ethylene/Methyl Acrylate	Few Grades, High Viscosity
Ethylene/Vinyl Acetate	Many Grades, Low Cost

From this list, the class of ethylene/vinyl acetate copolymers were selected for further development based on the following properties, (a) high optical transparency, (b) wide range of melt viscosities, (c) easy processing, (d) low modulus, (e) good adhesive properties, (f) moderate environmental stability, and (g) low cost.

EVA is a copolymer of ethylene and vinyl acetate typically sold in pellet form by DuPont Company and U.S. Industrial Chemicals, Inc. (U.S.I.). The DuPont trade name is Elvax; the U.S.I. trade name are Ultrathene and Vynathene. The cost of EVA typically ranges between $0.60 and $0.70 per lb (1980 dollars). All commercially available grades of EVA were examined(2) and final selections were based on transparency, melt viscosity and thermal stability.

Ethylene-Vinyl Acetate
Final Grade Selection

EVA Resin	Manufacturer	% VA	Melt Index
EY 901-25	USI	40	7.5
EY 902-30	USI	40	70.0
UE 645-35	USI	33	48.0
UE 638-35	USI	31	24.0
Elvax 150	DuPont	33	43.0
Elvax 170	DuPont	36	0.7
Elvax 240	DuPont	28	43.0
Elvax 250	DuPont	28	25.0

These final selections followed laboratory tests of optical transparency, thermal stability, photostability and ease of processing. Some general observations on the properties of EVA resins are:

(a) the vinyl acetate content must be in excess of approximately 25% in order to have acceptable optical transmission (89 - 92%),[b]

(b) the very high vinyl acetate copolymers (appx. 45% VA) have reduced thermal and light stability,

(c) as the vinyl acetate content increases the polymer flow point decreases and the surface tack increases,

(d) low melt flow compounds may be handled easily, high melt flow compounds exhibit agressive surface tack and adhere to most surfaces.

Based on film extrudability and transparency, the best choice became Elvax 150, at a cost (for high-volume purchases) of about $0.65/lb. Elvax 250 was a close second choice. Elvax 150 has the lowest melt viscosity that may still be handled without much difficulty in melt processing. Higher melt flow compounds could not be extruded and transported with film rollers due to their excessive surface tack.

(b) Efficient crosslinking improves transparency and may lower the required vinyl acetate content.

After selection of the base resin, Elvax 150, development efforts were directed towards the other pottant performance specifications. Elvax 150 softens to a viscous melt above 70°C, and therefore is not suitable for temperature service above 70°C when employed in a fabricated module. This was the first material deficiency that had to be corrected by formulation. A good pottant compound should have a low melt viscosity to impose little stress on the cells during lamination, but should cure at some point in the process to a thermoset resin that will no longer flow under heat. This property is required to prevent the flow of the pottant under solar heating that would result in damage to the module.

The other consideration was environmental stability. EVA, like all other polyolefins, is prone to photoxidation in the presence of air and sunlight. These conditions slowly degrade the unstabilized resin and result in discoloration and softening. Chemical compounds must be added to the EVA base resin to correct for these performance deficiencies in order to yield a viable pottant compound for solar module lamination.

C. Cure Chemistry

To function effectively, creep resistance (lack of flow) at the module operating temperatures is a necessity. To accomplish this requirement, the copolymers must be compounded with chemical additives that permit the resin to flow during the lamination cycle, but then subsequently crosslink (cure) at a later time. Crosslinking and/or vulcanization is defined as a process for converting a thermoplastic material into a thermosetting material that will no longer flow upon the application of heat. This process converts the majority of the polymer molecules into a single network which then retains many desirable physical and chemical properties of the base polymer under higher temperatures. Cure chemistry was accomplished with the use of an organic peroxide additive. The peroxide crosslinking of saturated polymers not only involves a large number of chemical reactions within the polymer itself, but also between peroxide decomposition residues, atmospheric oxygen (if present) and other additives compounded into the rubber. The predominant reaction that gives rise to the formation of crosslinks is referred to as hydrogen abstraction. The basic steps of this chemical reaction are:

(1) Peroxides thermally cleave to produce two oxy radicals Acyl peroxides yield acyloxy radicals; alkyl peroxide yields alkoxy radicals. $ROOR \xrightarrow{\Delta} 2RO\cdot$

(2) Oxy radicals are very reactive and abstract hydrogen atoms from polymer chains, where P= polymer. $PH + RO\cdot \rightarrow P\cdot + ROH$

(3) Two polymer radicals then combine to form a crosslink, resulting in cure. $2P\cdot \rightarrow P - P$

In polymers the degree of crosslinking varies depending on the type and number of hydrogens available for abstraction and the presence of other reactive groups. The degree of crosslinking is affected by (a) the polymer type: saturated, chlorinated, etc.; (b) the peroxide type: dialkyl, diacyl, peroxyester, etc.; (c) the processing parameters: peroxide concentration, thermal decomposition rate, temperature, time, and (d) the interaction with other additives such as antioxidants, fillers, oils, and stabilizers.

Dialkyl peroxides are generally the most efficient and most widely commercially used for polymer crosslinking applications. Their high activiation temperatures yields compounds of excellent thermal stability during compounding and reduced problems with "scorch" (premature curing). A wide variety of compounds are commercially available.

The factors guiding the selection of peroxide for the given application are as follows: (1) generation of crosslinks as the only modification of the polymer, (2) rapid decomposition at the desired cure temperature to yield efficient cure, but (3) survives the polymer compounding and processing steps, (4) effective in the presence of the other compounding ingredients such as antioxidants and UV stabilizers, (5) must be soluble in the polymer compound and preferably solid to prevent volatile losses, (6) is non-toxic before and after decomposition, and (7) does not sensitize the polymer to heat or ultraviolet light.

Peroxides containing aromatic groups (such as dicumyl peroxide) should be avoided due to their sensitizing effect on light stability.

Cure time and temperature can be determined in a peroxide cure system from knowledge of the rate of initially thermal decomposition. It is this reaction (homolytic cleavage and the generation of free radicals) that is the rate determining step in the curing or crosslinking sequence of reactions. The reaction follows first-order kinetics and is generally characterized by their half-life temperature. This term is more useful than "rate-constant" and is defined as the temperature at which fifty percent of the peroxide will decompose within a given time period. The half-life temperature is useful as an initial guide for the determination of processing safety and the selection of cure temperatures. The decomposition rate is independent of the amount of peroxide present, but does vary somewhat with the medium in which the decomposition is taking place. The thermal decomposition rates in polymer systems are usually slower (than in solutions) due to the reduced mobility of the resulting free radicals and the opportunity for recombination to occur.

In commercial practice, polymer cure conditions are often selected to obtain six or seven half-lives in order to insure complete peroxide decomposition and the maximum development of physical properties. The following table illustrates the relationship between the half-life and the percent of peroxide decomposition:

Number of Half-Lives	% of Original Peroxide Decomposed
1	50.0
2	75.0
3	87.5
4	93.75
5	96.9
6	98.4
7	99.2
8	99.6

In industrial practice, compounds are usually cured for at least three half lives at the selected cure temperature. Peroxides are efficient crosslinkers of polymers, however it must be pointed out that exposure to oxygen causes a competing reaction to occur that reduces the efficiency.

Due to the fact that most cures are done either in closed molds or in vacuum bag laminators the exclusion of oxygen is usually sufficient to prevent competing reactions. Curing openly in the presence of air, however, must be avoided.

A wide range of commercially available organic peroxides were evaluated as potential curing agents for Elvax-150. Of some twenty peroxide agents that were tested, only five were found to crosslink the polymer effectively. These compounds were blended into EVA copolymer (Elvax 150, DuPont) by cold milling at room temperature on a differential two roll rubber mill at a level of 1.5 weight percent. No other additives were incorporated. The resulting compounds were then cured by compression molding 20 mil thick plaques at a temperature of 150°C for twenty minutes. This basic test was useful for determi[illegible] if the basic cure chemistry of the peroxide was compatible with the resi[illegible]e following table indicates the relative effectiveness of the peroxides as judged by gel content (percent insolubles) and the swell ratio (indication of the crosslink density):

Peroxide Cures - Elva. 150 EVA

Peroxide[a]	% Active	Half-Life Temperature One Hour	Half-Life Temperature Ten Hours	Flash Point (Volatility)	Swell Index[b]	Gel Content[c]
Lupersol 331-80B	75%	111°	93°C	40°C	2,500	87%
Lupersol 99	75%	118°C	99°C	77°C	2,800	89%
Lupersol TBEC	100%	120°C	86°C	101°C	2,400	95%
D-S606	100%	96°C	76°C	77°C	3,200	69%
Lupersol - 101	100%	138°C	119°C	43°C	2,500	88%

(a) All are products of Lucidol Div., Pennwalt Corp. (b) In toluene (c) 150°C/20 minutes

The degree of cure required for use in solar module applications was determined in a separate experiment. It was found that cures in excess of 60% gel content resulted in compositions that were resistant to thermal creep at 110°C. It is felt that successful cure may be regarded as 70% gel content or better. Using this criteria, the following performance was found.

Peroxides: Time/Temperature Cure Determination

	Time Required for 70% Gel Content (a)				
Cure Temperature	120°C	130°C	140°C	150°C	160°C
Lupersol 101	N/A	N/A	45	15	6
Lupersol 99	30	20	12	8	2
Lupersol 331-80B	15	10	5	2	2
Lupersol TBEC	30	10	4	2	1

(a) Peroxides at 1.5 phr in Elvax-150

The preceding work represents experiments that were conducted over a three year period of time. When the need to cure the EVA was first recognized Lupersol 101 was the only organic peroxide available that was found to give satisfactory results. The other compounds, Lupersol 331-80B, 99 and TBEC were introduced a few years later. Due to this fact, two formulations of EVA have resulted, one based on Lupersol 101 (Springborn Laboratories No. A9918) and one based on Lupersol-TBEC (Springborn Laboratories No. 15295). Although these two compounds perform the same function, they do so through slightly different chemistry. The Lupersol 101 additive crosslinks the EVA exclusively through the vinyl acetate groups on the polymer, whereas the Lupersol TBEC appears to be active with both the polyethylene segments and the vinyl acetate groups. It has been found that if the vinyl acetate content is reduced to zero (pure polyethylene) no cure results with Lupersol 101, however Lupersol-TBEC is still capable of crosslinking activity. The time / temperature results indicate that, when compared to cure with Lupersol 101, the new peroxide, Lupersol TBEC, may be capable of resulting in equivalent cure in one third to one tenth the time, depending on the temperature selected.

Of the four efficient peroxides presented, Lupersol-TBEC currently appears to be the material of choice for EMA also, and should be considered as a replacement for the Lupersol-101 in future formulations. Its selection is based on: (a) it has the highest curing efficiency of the cross-linking agents examined to date, (b) it is 100% active, and (c) it has the lowest vapor pressure and is less prone to volatile losses.

The high degree of cure at a lower temperature that results with Lupersol-TBEC is also desirable due to the energy saving, and reduced time required for heat transfer during lamination.

Springborn Laboratories currently offers two commercial grades of EVA; the standard A9918 based on Lupersol-101 and the "fast cure" grade 15295 based on Lupersol-TBEC.

D. Antioxidant Selection

Polyolefins (such as polyethylene, polypropylene and EVA) are known to be sensitive to the combined effects of heat and air (oxygen). This process (oxidation) causes the polymer to degrade and loose some of its desirable properties, such as transparency, flexibility, gel content, tensile strength, etc. The process by which this happens is very similar to the free radical chemistry by which peroxides cure the polymer, however, now oxygen enters the reaction and alters its pathway. Once started, the chemistry may often cause a chain reaction of events that result in a rapid decline in the useful properties of the polymer. For this reason small quantities of additives that terminate the reactions (antioxidants) are used to stabilize polymeric materials.

Following the curing studies with Lupersol 101 peroxide, it was decided to perform a series of experiments to select an appropriate antioxidant. Formulations were prepared with different candidate antioxidants and molded into cured plaques that were subsequently heat aged in a circulating air oven. Each plaque also contained a disc of unprimed copper to examine any corrosion effects that might occur. The compounds were evaluated for cured gel content, gel density (tight or loose cure), color upon thermal aging and corrosion effects on the copper disc. The following table records the results. The compounds that could be rejected immediately were those that resulted in low gel contents indicating insufficient cure.

Antioxidant Study

(Elvax 150 Cured With Lupersol - 101)

Antioxidant	Level (phr)	Gel Density	Gel Content %	400 Hours @ 90°C Thermal Stability Color[a]	400 Hours @ 90°C Corrosion Effect on Copper[b]
Goodrite 3114[c]	0.2	low	17.6	1	2
Dilauryl Thiodipropionate	0.2	low	42.9	1	1
Polygard	0.2	high	78.5	1	1-2
Disteryl Thiodipropionate	0.2	high	78.3	1	2
Irganox 1076 [c]	0.2	high	76.9	1	4
Naugard P	0.2	low	69.4	1	1
Naugard P Irganox 1035 [c]	0.1 0.1	low	62.9	1	4
Irganox 1010 [c] MD 1024	0.1	high	87.4	1	3
Control - no AO	0	high	92	2	2

a. Thermal evaluations performed by subjective assessment of color formation:

1. No color formation	2. Very light color	3. Light color
4. Noticeably yellow	5. Bright yellow	

b. Corrosion also determined by color of ring around copper molded into polymer.

c. Phenolic compound, possibly causing UV sensitization. Omitted from selection Omitted for low gel content; No.'s 1, 2.

The antioxidants were compounded into a complete formulation to include any antagonistic effects that could occur from other ingredients. A slightly lower level of peroxide (0.75 phr) was used to accentuate the free radical inhibition effect of the antioxidant(a).

(a) Antioxidant and peroxide curing agents are normally antagonistic, however the benefits of both may result if they are <u>kinetically</u> dissimilar. The peroxide must "swamp" the antioxidant with radicals during cure, and the antioxidant should be capable of slow long term radical termination during the service life.

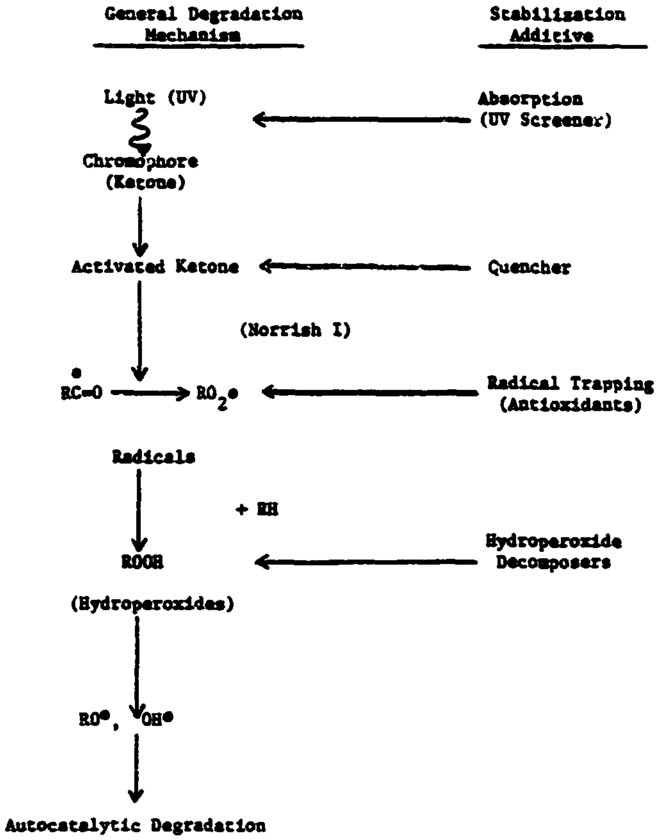
The best overall performance was found for Naugard-P. This compound gave high gel contents, no corrosive attack to the copper disc. After 400 hours at 90°C the polymer specimen showed no signs of color formation and no ring could be seen around the copper disc. A distinct advantage to the use of Naugard-P is that it is not a phenolic compound and, therefore, does not give rise to UV sensitization and possible degradation of the polymer. Chemically, Naugard-P is an alkyl aryl phosphite, a high viscosity transparent fluid. This compound, although a first-cut selection, was used in the Lupersol-101 formulations of EVA that followed. In the advanced cure EVAs based on TBEC peroxide the antioxidant was eventually eliminated and replaced with another additive.

E. Photostabilization

Virtually all polymers (except perfluorocarbons and silicones) are prone to degradation caused by exposure to sunlight. The component of sunlight largely responsible for this chemistry is high energy low wavelength region in the ultraviolet. This region comprises the wavelengths from 290 nm to about 400 nm, in the blue end of the spectrum. The mechanisms responsible for the deterioration depend on the polymer involved, however they are all initiated by the presence of a "chromophore", or group capable of absorbing the light energy. These groups consist of shifting double bond structures and typically include azo (N=N), ene (C=C), carbonyl (C=O) , and aromatic groups. Polymers that do not contain these groups as part of their structure still contain chromophoric impurities which make them susceptible to attack. Examples are polyvinyl chloride, polypropylene, polyethylene.

When this high energy light is absorbed an excited state results in the molecule that (unless dissipated) results in a sequence of events that breaks the chemical bonds in the polymer. The rupture of these bonds generally (a) fragments the molecular chain so that the original properties of the polymer are lost, and (b) generates free radicals that result in a propagating chain reaction that further accelerates the degradation. The result is often embrittlement, discoloration, flow, softening, or other loss of physical property. The general chemical mechanism is as follows:

Photodegradation in Polyolefins



This diagram represents the chemical mechanism of degradation on the left side, and the additive used to interrupt this chemistry on the right side.

Many stabilizers are commercially available that perform these protective chemistries. In a pottant application not all of these additive compounds may be used. The requirements for an additive are: (a) must be transparent in the wavelength range of solar cells sensitivity, (b) must be mix compatible with the polymer EVA, (c) must be efficient in their action, (d) must not interfere with the cure chemistry, and (e) must retain their activity throughout the intended service life of the polymer.

a. UV Absorbers

Ultravilolet absorbers are the most frequently used additive for imparting photostability in polymers, and are frequently used in the 0.1% to 0.5% level. UV screeners function by preferentially absorbing the ultraviolet component of sunlight and converting it into heat via a temporary molecular rearrangement. Several chemical classes of absorber compounds are known, one of which, the benzophenones, is known to be particularly effective in polyolefins such as EVA. From a study of manufacturers literature and the results of RS/4 aging tests at Springborn, an absorber was selected that appears to be optimum for this system. This compound is Cyasorb-UV-531 and is available from American Cyanamide, Bound Brook, N.J. To date, this additive has performed extremely well and is used at a level of 0.3 parts in the formulation.

b. Hindered Amine Stabilizers

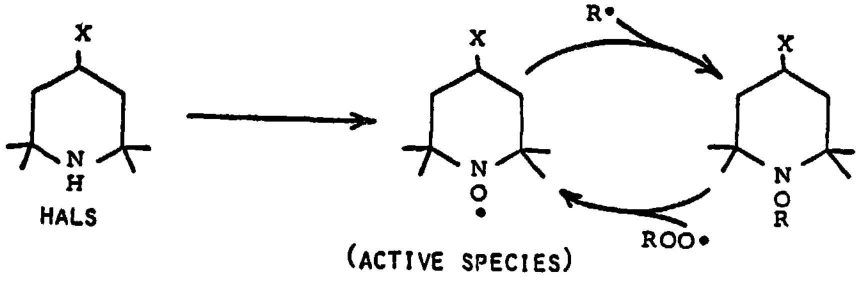
Despite the effectiveness of ultraviolet absorbers a certain amount of light may still enter the polymer, especially at the surface. The chemical events caused by the remaining fraction of absorbed light may be intercepted by the addition of a second stabilizer. This stabilizer may function by interacting with any of the chemistries that follow the absorption of light, i.e. excited state quenching, free radical trapping and hydroperoxide decomposition.

Quenchers function by accepting the excited state energy from an activated chromophore group in the polymer. The result is that the polymer returns to a chemically stable ground state and leaves the quencher in the excited state. The quencher then dissipates the energy as heat through a series of transitions on the way back to ground state. Most quenchers are based on highly colored metal complexes that would reduce the optical transmission of the pottant, consequently they were not explored for this use.

Free radical traps are compounds capable of reaction to yield non-free radical by-products, and consequently interrupt the autocatalytic propagation steps that lead rapidly to degradation. Antioxidants generally operate in this manner and are sacrificial. As the free radical reactions continue to be initiated, the antioxidant molecules are gradually consumed until the polymer is left unprotected. Antioxidants are also known to protect ultraviolet stabilizers from oxidation, consequently the presence of both stabilizers is not only additive, but sometimes synergistic.

When a light induced free radical event occurs in a polymer atmospheric oxygen frequently intervenes in the following manner: $R^{\cdot} + O_2 \rightarrow R\text{-}O\text{-}O^{\cdot}$. This group may now abstract a hydrogen from a neighboring polymer to give a somewhat stable hydroperoxide, R-OOH, and leave another reactive site on the other polymer chain. This process repeats itself and is referred to as "photo-oxidation". Although the initiating radical may be deactivated by trapping, the residual hydroperoxide group is unstable in the presence of heat and light and may decompose to form new radicals that start the process over again. Hydroperoxide decomposers are reducing agents that chemically react with the hydroperoxides to yield stable non-radical products such as R-OH, and H_2O.

One class of compounds, the hindered amine light stabilizers (HALS), have been found to be remarkably effective in performing both radical trapping and hydroperoxide decomposition. In addition, these compounds enter a cycle of regeneration such that the species that traps free radicals is reactivated in the process of decomposing a hydroperoxide group. This results in an extremely effective and a non-sacrificial stabilizing activity. The general reaction may be represented as follows:



The HALS product selected for use in commercial evaluation versions of EVA is Tinuvin-770, a product of Ciba-Geigy Corporation, Ardsely, New York. The compound is a free flowing white powder and is incorporated into the EVA base resin at a level of 0.1 parts per hundred parts of resin. Synergistic stabilization resulting from the use of Tinuvin-770 and Cyasorb UV-531 has been reported in the recent literature(c) and the effectiveness of these additives is also apparent from the outstanding stability of the resulting formulation.

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c) Allen, Journal of Applied Polymer Science, Vol. 27, page 2761 (1982)

F. Formulation, Compounding and Extrusion

Any material to be used in the construction of solar modules must first be formulated to have the required physical, thermal, optical, and electrical properties, but second must be available in a form that is suitable for fabrication. In order to use polymeric materials as pottants, it is necessary that the physical form of the polymer be appropriate to the encapsulation technique being employed.

The work on curing agents, antioxidants and ultraviolet stabilizers has resulted in two formulations to date The first formulation employs Lupersol 101 as the curing agent, and the second is a faster cure version based on Lupersol-TBEC. The formulations are:

Commercial EVA Formulations(d)

Compound	A9918	15295	Form	Supplier
Elvax 150	100	100	Pellets	DuPont
Lupersol 101	1.5	-	Liquid	Lucidol/Pennwalt
Lupersol TBEC	-	1.5	Liquid	Lucidol/Pennwalt
Cyasorb UV-531	0.3	0.3	Powder	American Cyanamide
Naugard-P	0.2	0.2	Liquid	Uniroyal
Tinuvin-770	0.1	0.1	Powder	Ciba-Geigy

Laboratory investigations showed that these ingredients may be blended (compounded) easily in the melt phase and trial formulations were easily prepared using a differential two-roll mill. This method works well for small batches (100-500 grams),however it could never produce the amount of compound required for production purposes. In production, an extruder is required to convert the polymer formulation into a sheet form suitable for cell lamination. Since the extrusion process passes the polymer through its melt form, it was decided to combine the extrusion and compounding steps into one operation so that blending of ingredients occurs in the extruder. Techniques for the large scale production of EVA sheet were devised using this method.

(d) EVA A9918 is the standard commercial grade of EVA lamination material; 15295 is the "fast cure" grade.

In production, a mixture of ingredients must be prepared first to give "hopper feed" for the extruder. Barrel blending was found to work well. One hundred pound lots of the clear EVA compound are easily prepared by taking the ingredients as listed in the formulation and simply tumble blending them in a rotating drum. The liquid ingredients disperse over the surface of the EVA pellets in this process and cause the powdered ingredients to adhere in a uniform layer. After half an hour of tumble blending the resulting mix can be used directly a "hopper feed". No inhomogenity can be noticed in the final product and the extrusion process yields a thorough blend.

Preliminary conditions established in the laboratory were then used towards a large-scale pilot plant production. A major extrusion effort was conducted using a Hartig 2-1/2 inch extruder with a general purpose single-stage screw. In the extrusion process heat is applied to the feed zones (1 and 2) in order to develop a melt plug that forces the resin along the screw towards the die. Most of the compounding occurs in the mix and compression zones (4-8),and the temperature in this region is kept low enough (below 120°C) to prevent premature crosslinking of the resin and decomposition of the peroxide. Extrusion at the die seems to give the best results at about 75°C.

The following lists the average extrusion conditions found for both resins; A9918 and 15295.

EVA Extrusion Conditions

Equipment:	Hartig 2-1/2 inch extruder w/single stage polyethylene screw. 24:1 L/D Screw compression ratio; 3.5:1, water cool option. Screen Pack: 20, 100, 80, 20 mesh Die width: 32 inches - full web

Temperature Profile:

	Barrel						Die		
Zone	1	2	3	4	6	8	9	10	11
Set Temp. °C	88	93	93	80	80	80	75	75	75
Run Temp. °C	90	98	105	115	115	115	80	75	75

Take-up Rolls: Roll No. 2 - 28°C : Rolls 3, 4 approximately 15°C
Pack Pressures: 2600-3400 psi
Screw Speed: 36 rpm (22%)
Speed, Extrudate: 6.4 - 6.5 feet/minute, 24 inch width
approximately 110 lb/hr.
Thickness: 18 mils ±1 (clear), 14 mils ±1 (white)

Extrusion proceeds smoothly with no difficulties, and a slow water trickle through screw appears to be effective in maintaining the temperature below 120°C. The difference between the set and run temperatures is due to the shear heating that results from mechanical working of the polymer. The extruder heaters are thermocouple controlled types and switch off when they reach the desired temperature. After the extrusion process has run for awhile these heaters spend most of their time in the "off" mode and the extrusion procedes under ambient conditions. Using a dye marker, the residence time of the polymer in the extruder (from feed zone to die) has been found to be in the order of three minutes. This short time and the relatively low temperatures results in very little peroxide decomposition and no premature curing of the polymer. The same conditions are used for both polymer formulations, however the 15295 compound is much more sensitive to hot spots and high shear zones should be avoided. The temperature should always be measured directly in the melt stream and there should be some provision for cooling the barrel if the heat build-up becomes excessive.

The sheet extrudes at a rate of about 8 feet per minute and is taken up on chrome rollers cooled to 5-10°C. The thickness is uniform across the 24 inch wide sheet at 0.018" ± 0.01". The sheet is wound on cardboard cores with release paper interleaving. The interleaving is necessary to prevent the wound sheet from "blocking" or sticking to itself so that the plies are difficult to separate. The use of an embossing roller to put a surface texture on the EVA sheet has been explored and found to be an effective way to prevent the EVA plies from sticking to each other. With the embossed surface, the release paper may be eliminated and the sheet winds and unwinds without difficulty. This technique has a drawback, however. The embossing process compresses the film during extrusion and builds in a certain amount of mechanical stress in the width direction. When the EVA sheet is reheated during module fabrication stress relaxation occurs and the polymer tends to shrink inwards. This has been found to shift the cells and throw them out of register during lamination. This problem is avoided with the use of the release paper separator method.

G. Cured Properties

Adequate curing of the EVA formulation is an essential part of its successful use as a solar cell potting compound. The curing chemistry results from a combination of time and temperature that may be estimated from the peroxide thermal decomposition curve (Figure 1 , Appendix). Due to the interactive and competing chemistries that occur in formulated compounds, laboratory experiments were conducted to determine the time temperature relationship empirically. Samples of extruded resin were placed in a heated platten,pressed at known temperatures, and removed at predetermined times. The cured resin was then tested for gel content in order to determine the degree of cure. The resulting gel contents, times and temperatures are given in the following tables:

Gel Contents
EVA Formulation A9918

Time Minutes:	110°C	120°C	130°C	140°C	150°C	160°C
2				1.0	4.1	29.5
5			0	11.8	21.1	73.0
10	0	0	1.0	23.5	63.2	82.6
15	0	0	2.3	59.3	88.3	
30	0	0	3.4	68.2		

Gel Contents
EVA Formulation 15295

Time Minutes:	110°C	120°C	130°C	140°C	150°C	160°C
2			0	73.4	81.5	84.2
5			60.3	83.7	88.6	91.0
10	0	0	75.0	88.2	91.6	92.3
15	0	0	85.0	90.2	93.5	
30	0	65.0	82.7	92.2	92.6	

These results represent laboratory cures in which the heat transfer may be assumed to be instantaneous, however they should still be useful for estimating processing conditions used in module fabrication. As can be seen, the formulation using TBEC peroxide (15295) is significantly faster than the A9918 and also permits effective curing at lower temperatures. The degree of cure as determined by gel content (percent insolubles) may be determined by a simple laboratory procedure, as follows:

GEL CONTENT DETERMINATION

(1) Remove a small piece of cured EVA (1 to 2 g) and weigh on an analytical balance to three decimal places.

(2) Place the specimen in 100 ml of toluene and heat to 60°C for 3 hours.

(3) Pour the mixture through a piece of weighed filter paper to catch the gel fraction and permit it to drain completely.

(4) Dry the filter paper and gel fraction at 60°C for 3 to 4 hours (no odor of toluene solvent should remain).

(5) Weigh to three decimal places and subtract the weight of the filter paper.

(6) The gel content is calculated as:

$$\%\ \text{gel} = \frac{\text{weight of EVA residue from toluene}}{\text{weight of original EVA specimen}}$$

(7) EVA with gel content over 65% may be regarded as acceptably cured.

The described laboratory lamination process has resulted in gel content consistently ranging from 75% to 80%.

The adequate curing of EVA also results in a change in some of the other measurable properties. A summary of these is tabulated as follows:

EVA Properties Summary

	Elvax 150[(c)]	A9918[(d)]	15295[(d)]
Ultimate Tensile Strength, psi[(a)]	850	1,890	3,630
Ultimate Elongation[(a)]	1,050	510	575
Secant Modulus (1% Strain)[(a)]	850	890	755
Optical Transmission[(b)]	90.5	91.0	92.0
Glass Transition Temperature, °C	-43	-43	-43
Hardness, Shore A	65-73	76-79	70
Density, g/cm^3	0.957	0.920	- -
Refractive Index	1.482	1.482	1.479
UV Cutoff Wavelength, nm	290	360	360
Gel Content, %	0	75	75

(a) ASTM D-638

(b) ASTM E-424

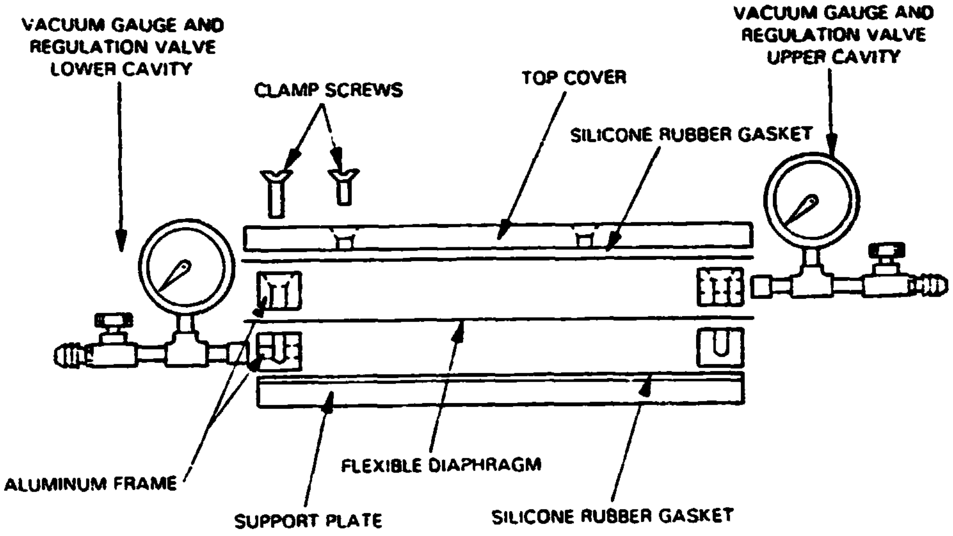
(c) Uncured natural resin

(d) Fully cured compounds

H. Module Processing

A successful and predictable module-fabrication process for EVA pottant has been achieved through a double vacuum-bag technique. To implement this technique, a special piece of equipment was built. The apparatus, schematically shown on the following page consists of a double-sectioned aluminum picture frame, closed at the top and bottom by aluminum plates. A flexible polymer diaphragm separates upper and lower cavities, and also function as a vacuum-tight gasket. Each chamber has its own vacuum gauges and valves for its individual evacuation. The top-cover plate is permanently attached and sealed to the top cavity with bolts and a silicone rubber gasket. The lower plate is removable and seals to the bottom of the lower frame piece with a silicone-rubber O-ring gasket.

The diaphragm material used is a high-temperature nylon film, 0.003 inch thick, which is flexible, but not elastic. Conceivably, other types of films would work well in this application.

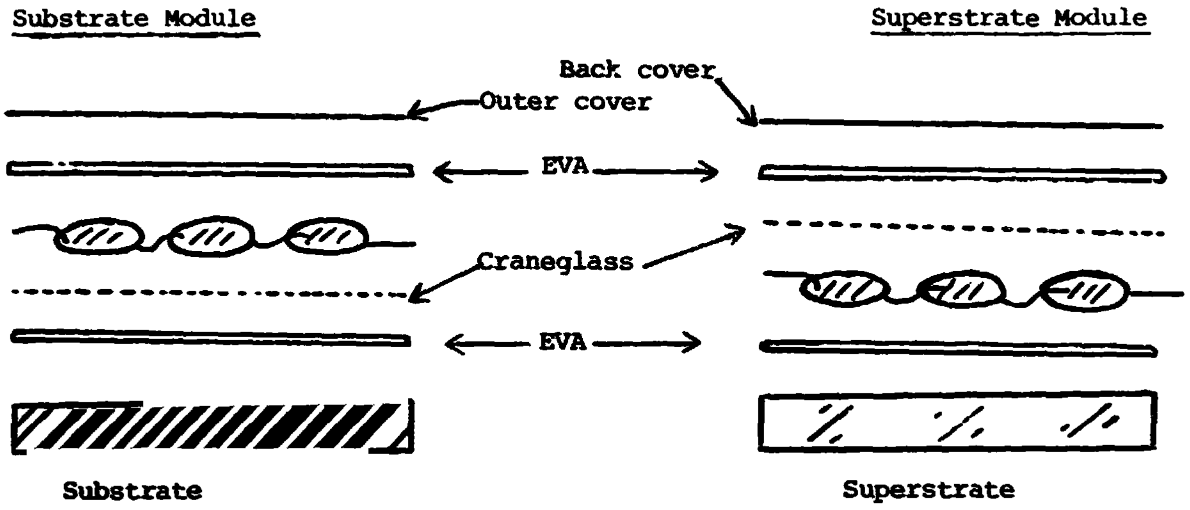


Vacuum Bag Laminator

The module assembly is placed under the flexible diaphragm, in the lower cavity. The top surface of the module assembly is positioned flush with the top edge of the lower cavity, by stacking a necessary number of thin metal plates in the bottom of the lower cavity. The double vacuum-bag design enables initial exposure of the module assembly to a vacuum without simultaneous compression of the diaphragm, thus greatly enhancing air exhaustion from the module assembly. To ensure thorough air exhaustion, especially from large-area modules, the use of air-release scrim sheets of material such as Craneglas should be incorporated in the module assembly.

Diaphragm compression of the module assembly can be done at any stage of the lamination cycle by pressurizing the upper cavity. Compression should be initiated or achieved, however, before the temperature of the EVA reaches 120°C.

In practice, the module components are preassembled into a sandwich before the encapsulation step. The basic assembly of materials required for vacuum-bag processing of substrate and superstrate modules are shown .



Once the basic module components for either design have been assembled, a 10-mil-thick fluorinated ethylene propylene (FEP) release film,or an equivalent,should be included above and below the assembly. The release films should be cut to match the area of the module. These outer FEP film layers are then taped together over the edges of the module assembly with masking tape to contain the EVA when it softens during the heating cycles. The wrap-around of masking tape is attached to the FEP film layers, rather than to surfaces of the module. Although the edges are taped firmly, entrapped air seems to diffuse out easily.

An additional fabrication aid is to include two 5-mil-thick (or thicker) metal (steel or aluminum) plates, one on each side of the taped module assembly. These plates distribute the lamination pressure over the module area, and result in uniformly thick modules, with smooth, wrinkle-free back-cover or front-cover surfaces.

The completed module assembly with taped edges is then placed in the lower cavity of the laminator and a microthermocouple is taped onto the FEP release film at the module center. The thermocouple permits convenient monitoring of the module temperature during the lamination cycle. The flexible diaphragm and upper-cavity fixtures are then positioned.

Both the upper and lower cavity are evacuated at room temperature for 5 to 10 minutes before heating, to exhaust the air from within the module assembly. While maintaining continuous vacuum in both the upper and lower cavity, the entire vacuum-bag fixture is loaded between the preheated (150°C) platens of a hydraulic press, which serve as the heat source. The ram pressure is just sufficient to close the press and provide good heat transfer to the vacuum-bag fixture. The pressure from the platen should rest only on the frame of the fixture and should not contribute any pressure to the surface of the module.

In this process, pressurization of the upper cavity to 1 atm of pressure is initiated when the module assembly temperature reaches 120°C. The double-vacuum-bag fixture provides a capability of limiting pressurization in the upper cavity to less than 1 atm. However, low-pressure (< 1 atm) lamination has not yet been experimentally investigated to determine the effect of pressure in inhibiting gas-bubbles formation due to peroxide decomposition.

The time-temperature heating pattern of the module assembly after loading the vacuum-bag fixture into the preheated hydraulic press is shown in Figure 2 . Experimentation with this heating process has demonstrated that a dwell time of 10 minutes at 150°C results in an acceptable EVA cure (less than the 20 minutes determined in the laboratory testing). The reduced dwell time reflects the degree of partial curing that occurs during the heat-up time to 150°C (faster or slower heating rates may require adjustment of the dwell time at the peak cure temperature). Samples of EVA taken from modules laminated by this process and associated time-temperature heating patterns exhibit acceptable cure with gel contents over 75%.

After the 10-minute dwell at 150°C, the laminator can be removed from the heating press and permitted to cool in still air. When a temperature of about 40°C is reached, the vacuum in the lower cavity may be released, and the completed module may be removed from the laminator.

Modules prepared by the preceding process have been fully cured, and are bubble-free and of good appearance. No evidence of cell damage has been noticed.

Lessons learned from the laboratory development indicate that an industrial-scale EVA lamination method must:

(1) Prevent exposure of the EVA during heating to atmospheric oxygen, which was found to interfere chemically with the cure.

(2) Hold the module components physically in place (above 70°C, and before cure above 120°C to a tough elastomer , the EVA is in a fluid state).

(3) Apply uniform pressure over the surface area of the module during the high temperature cure stage.

(4) Maintain constant vacuum for air and gas removal.

(5) Use air-release spacers (e.g., Craneglas) in the module assembly to facilitate total air removal from module interfaces.

H. Aging Behavior

As with all polyolefin polymers, EVA is known to have certain aging properties. The causes of aging are heat, oxygen, and light. In addition to these basic aging stresses, there is also the possibility of catalysis by other materials that cause the aging effects to be accelerated. Metal ions are known to have this effect. During the development of EVA certain tests were performed to assess the relative stability and aging behavior of EVA and discover the limitations of its use. Experiments were conducted in which test specimens of EVA were exposed to individual and combined stresses and the change in properties monitored with time. The first experiments concerned thermal aging.

a. Thermal Aging

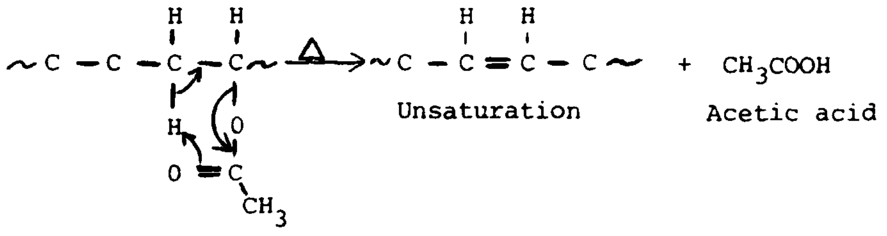
Although this method is simple in concept and easy to implement there are certain potential sources of error that should be considered prior to running the tests. For example, forced air ovens may result in an abnormally rapid rate of loss of the antioxidants and other compounding ingredients.

Even stabilizers of reasonably high molecular weight are subject to loss by evaporation and continual extraction by the air stream.

Two general types of thermal degradation may take place in the polymer systems of interest; (a) thermal oxidation, in which a chemical reaction occurs between the polymer and oxygen in the atmosphere, and (b) thermolysis, in which the energy provided by heating causes a change in the chemical structure of the resin by itself.

In the thermal aging tests at Springborn, the encapsulation test specimens are aged in sealed jars to prevent loss of stabilizer, cross-contamination of compounds, and also to provide aging in atmospheres of both air and nitrogen.

The purely thermal degradation of ethylene vinyl acetate resins, in the absence of oxygen and water vapor, proceeds by the conversion of acetate groups to acetic acid, followed by crosslinking at the resultant sites of unsaturation, and ultimately crosslinking. The chemistry may be represented as follows:



The thermal degradation rate versus temperature for the conversion of acetate groups to acetic acid is shown in Figure 3 which is reproduced from DuPont Technical Bulletin 0820.2. Significant conversion only occurs at very high temperatures, which can occur during certain high-temperature processing operations, but that at temperatures close to ultimate rooftop temperatures, 85-90°C, the conversion rate is an almost negligibly low value of 6.3×10^{-10}% per minute (log k = -9.2). If the EVA were sustained continuously at 85-90°C for 20 years in the absence of oxygen and water vapor, this would correspond to a net conversion of only 0.006%

of the acetate groups to acetic acid. On an absolute weight basis, 20 years would correspond to an acetic acid accumulation of less than 0.002 wt % in EVA pottant. A hermetic module design comprising a glass superstrate and a metal-foil back cover essentially would isolate the EVA pottant from exposure to atmospheric oxygen and water vapor, and with only a few hours per day at which the module would be at rooftop peaking temperatures, a problem associated with acetic acid generation over 20 years appears remote. No problem is expected with a hermetic module design at array peaking temperatures of 55°C to 60°C. The following table gives the results of thermal aging at 70°C, 90°C and 130°C and up to 7,200 hours of exposure time.

Thermal Aging
of Cured A-9918 EVA in Circulating-Air Ovens

Time	Property	70°C	90°C	130°C
1 wk	Tensile, lb/in.^{2}	2685	2200	2000
(168 h)	Ult. elongation, %	595	550	550
3 wks	Tensile, lb/in.^{2}	1700	1800	1240
(504 h)	Ult. elongation, %	670	680	638
2 mo	Tensile, lb/in.^{2}	2370	2660	1320
(1344 h)	Ult. elongation, %	600	784	647
10 mo	Tensile, lb/in.^{2}	specimen	2120	144
(7200 h)	Ult. elongation, %	lost	660	37
	Gel content, %		91%	88%
	Color		clear, no yellow	brown/ orange
	Optical transmission, %		91%	74%
	Tangent modulus, lb/in.^{2}		833	335

Control (Unaged)

Tensile, lb/ in.^{2}	2160
Ult. Elongation, %	677
Optical Transmission, %	91
Gel Content, %	91

b. Photothermal Aging

Springborn Laboratories has exposed Elvax 150 and cured A-9918 EVA to UV light at 50°C. The UV light source is a General Electric RS/4 sunlamp, which if filtered to remove nonterrestrial wavelengths below 300 nm. The UV spectra and intensity from these lamps at the sample location have been measured and when compared with the peak intensities of AM 1.5 natural sunlight, correspond to an average UV intensity of about 1.4 suns. If it is assumed that typical values of total annual UV insulation in the United States were delivered at AM 1.5 peak intensities, this would correspond to about 5 hours per 24-hour day to deliver the total annual UV insolation. Defining a 1-sun UV-day as 5 hours in each 24-hour day, then about 1300 hours of exposure to these RS/4 sunlamps operating at 1.4 suns UV intensity represent one year of outdoor UV exposure. An exposure temperature of 50°C was selected to match array peaking temperatures. Atmospheric moisture in the RS/4 test chambers is that associated with the laboratory environment, typically at a relative humidity of about 50% to 60% at 25°C.

Exposure of unprotected Elvax 150 to RS/4 UV at 50°C results in a visible onset of yellowing after 1000 hours which continues and becomes more intense with continued exposure. The surface of this material becomes sticky and the physical shape of the specimen eventually shows a tendency to flow. The specimen is untestable after 1,500 hours. Exposure of an Elvax 150 sample crosslinked with 1.5 phr of Lupersol 101 (no stabilizers) essentially paralleled the aging behavior of the uncrosslinked Elvax 150. The major difference was gener 1 retention of its initial physical form, presumably due to crosslinking. Deterioration involving yellowing and surface stickiness also resulted in termination of this aging test at 1500 hours. Crosslinking of Elvax 150 alone is insufficient to stop or suppress the action of UV photooxidation.

Specimens of cured and fully compounded A-9918 EVA were also exposed to RS/4 UV at 50°C. No additional UV-screening films or covers were used. This exposure test involved two different lots of cured A-9918 EVA. As a trial experiment, a small piece of cured A-9918 EVA was exposed to RS/4 to visually assess the aging behavior of this material. When this sample passed 3000 hours of exposure without any visual changes, it was decided to initiate exposure of a larger quantity of cured A-9918 specimens in order to monitor optical and mechanical properties as a function of aging time. The initial specimen, designated Lot 1, was left in the RS/4 chamber to continue accumulating exposure time, and the new batch of cured A-9918 EVA specimens were designated as Lot 2.

The optical and mechanical properties of Lot 2 A-9918 EVA, with up to 27,000 hours of exposure are given in the following table. At 27,000 hours there was very little change in the measured properties of the cured A-9918 EVA. The sample removed for testing was clear, had no visible indications of any yellowing, was firm and non sticky to the touch, and exhibited no change in its physical form. The Lot 1 sample, having then accumulated 30,000 hours of exposure time, was also clear, with no indications of degradation.

The Lot 1 material was finally terminated at a total of 40,000 hours of exposure at which point a faint yellow color and small surface cracks had appeared. The measured mechanical properties were still unaffected.

Accepting that 1300 hours of RS/4 exposure at 50°C equates to 1 year of outdoor exposure at 50°C, then 27,000 to 30,000 hours would correspond to more than 20 years of outdoor UV exposure. For an array installation having a peaking temperature near 55°C, there RS/4 data trends strongly indicate the potential of 20-year service life for cured A-9918 EVA.

The test results from the RS/4 exposures are tabulated on the following page.

Properties of Cured A-9918 EVA as a Function of Exposure Time to RS/4 UV at 50 °C

Lot 2 Specimens	Total Integrated Limit Transmission[a], %	Tensile Strength at Break, lb/in^2	Elongation at Break, %
Control	91.0	1890	510
2,880 h	91.0	1930	631
5,760 h	90.5	1340	550
8,640 h	90.0	1460	590
15,120 h	90.0	1520	570
27,000 h	90.0	1870	560
Lot 1 Specimens			
30,000 h	(b)	1450	480
35,000 h	(b)	1480	864
40,000 h	(b)	1479	714

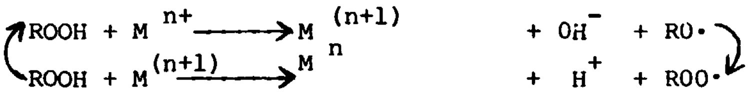
(a) Measured over 350 nm to 800 nm in 50 nm band increments

(b) Insufficient specimen available

c Metal Catalysis

Many metals having two or more stable oxidation states are known for their ability to degrade polymers. Copper is particularly well known for having a "pro-oxidant" activity in polyolefins and results in rapid acceleration of normally slow oxidation rates. This effect is of concern in the wire and cable industry where olefin resins are molded over copper conductors and a whole class of polymer additives known as "metal deactivators" have been developed in order to inhibit this effect.

The presence of multivalent metals in polymers is believed to induce or accelerate auto-oxidation in polymers by forming unstable coordination complexes with polymer hydroperoxides. These hydroperoxides then react with the metal ion via an oxidation-reduction mechanism to give free radicals which subsequently accelerate the degradation process. The catalytic effect comes from the fact that the metal ion results in the production of free radicals from both high or low oxidation states and therefore "recycles" as shown:



$$\begin{aligned} ROOH + M^{n+} &\longrightarrow M^{(n+1)} + OH^- + RO\cdot \\ ROOH + M^{(n+1)} &\longrightarrow M^{n} + H^+ + ROO\cdot \end{aligned}$$

Very small amounts of soluble copper ions in the polymer may have a dramatic effect on the oxidation rate. Metal deactivator are usually "chelating" compounds that are thought to operate by two modes; firstly, complexing the copper ion in the polymer and rendering it chemically inactive, and secondly, by forming a "passivation" layer on the surface of the exposed metal. Although some of these compounds appear to work quite well, it is generally acknowledged that the polymer that is not exposed to catalytic metals is still more stable than the polymer that is exposed to the metal and has a deactivating additive.

The pottant used in encapsulating PV modules will come in direct contact with metallic conductors on the front and back sides of the cell. Consequently, the possibility of chemical reaction, especially at high temperatures, exists.

Due to the use of metals (and possible use of copper) as exposed conductors in PV modules, a series of experiments were performed to assess the seriousness of this condition. In the thermal aging program, metal "corrosion" specimens were included in all conditions (60°, 85°, 105° and 130°C) and consisted of strips of copper, aluminum, and 60/40 lead/tin solder. Even at the highest temperature,and at the longest times,no adverse effects were noticed with the aluminum or solder. The copper proved to be very catalytic, however, and resulted in discoloration of the host resin and rapid deterioration of physical properties.

Due to this observation, a series of experiments on metal deactivation were conducted to determine if this effect could be inhibited through the use of deactivator compounds or possibly by silane passivation of the copper surface.

Test specimens were prepared by molding the candidate resin formulation over a copper screen to yield a coupon that could be monitored by spectroscopy. The earliest quantifiable sign of polymer degradation (non-destructive) is yellowing, which is most easily monitored by measuring the percent transmission at 450 nm. The use of copper screen permits the resin to come into intimate contact with the resin and still be monitored by transmission measurements. All resins were crosslinked with 1.5 phr of Lupersol-TBEC and 0.2 phr of a metal deactivator (except the control). Two metal deactivators were evaluated, MD-1024 (Ciba Geigy) and Cyanox 2379 (American Cyanamid). The Cyanox 2379 is not a commercial product, however it was evaluated following a literature search that indicated it to be the most effective deactivator for polypropylene yet discovered. The test specimens were measured for color change and visible changes after thermal aging at 105°C in both air and nitrogen. The results are shown on the following page.

Metal Deactivator Evaluation

Polymer	Deactivation	Lifetime, hrs.
EVA (air) (crosslinked w/1.5 phr TBEC)	None	650
	+ Silane	840
	Cyx 2379	990
	MD1024	1150
	MD1024 + Silane	1024
	Cyx 2379 + Silane	1320
(nitrogen atmosphere)	Cyx 2379 + Silane (15299-3B-N$_2$)	> 8500

As may be seen, silane treatment of the copper appears to provide a chemical barrier that aids in the corrosion decoupling of the polymer and the metal. Additionally, silane treatment of the copper appears to improve the effectiveness of the metal deactivator synergistically and further extend the lifetime. The least metal catalyzed oxidation was found for those specimens including both metal deactivator and silane treated copper.

All of the specimens initially included in this test have failed, except for one compounded with 0.2 phr of Cyanox 2379 metal deactivator and the copper screen treated with Z-6030 silane. The specimen has been aging in a nitrogen atmosphere for 8,500 hours with some yellowing of the polymer and no signs of corrosion in the vicinity of the copper. This is remarkable in comparison to the lifetime of the other specimens.

When compared to plain thermal aging without the presence of copper, it may be concluded that deactivators may help retard the pro-oxidant effect. However, the absence of exposed copper will be required for long lifetimes of polymers serving as pottants at rooftop array operation temperatures.

Due to the possible acceleration of thermal oxidation effects by multivalent metals, other metals should be screened for activity. To date, no adverse reaction have been found with the high temperature exposure of candidate pottants to aluminum, lead-tin solder (60/40), silver, nickel or titanium.

d. Aging Summary

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

Observation of Elvax 150 suggests that the UV wavelengths deleterious to this material, and necessary for UV photoxidation, are those shorter than 360 nm. Isolation of Elvax 150 from these UV wavelengths, with UV-filtering outer covers and/or compounding additives such as Cyasorb UV-531, stops UV photooxidation, and effectively reduces the aging characteristics of Elvax 150 to purely thermal effects.

The thermal effects encountered in module applications do not appear to be severe enough to cause any detectable degradation, consequently the property compounded material should have indefinite stability. The results of accelerated aging conditions verify this conclusion. A brief summary of observations and conclusions concerning the aging of formulated EVA pottant compound follows:

1. The first property to change appears to be color. Mild yellowing is detected prior to any measurable change in any other property.

2. At 50°C EVA appears to be naturally resistant to thermal aging, or undergoes a negligibly slow reaction. Even at a very severe 130°C, several months are required before there is much of any measurable change in physical properties.

3. Protection from photothermal events is required and the use of a benzophenone type UV screener with a HALS type stabilizer results in excellent performance.

4. The potential service life of EVA is most likely limited by the permanence of the stabilizer package and design considerations should minimize the possibility for loss of these stabilizers vs thermal evaporation or rainwater extraction.

5. In terms of modeling, the degradation curves are predominantly "induction period" type, in which the properties begin to degrade after a long period of stability. The decay of measurable physical properties does not resemble first-order behavior.

6. RS/4 exposure has been found useful for the accelerated aging of polymers, however it is only practical for marginally stable compounds. Exceptionally stable compounds, such as EVA 9918, take four to five years to degrade and consequently it takes a long time to obtain experimental results.

7. RS/4 - 85°C: despite the increase in temperature, the candidate pottants still perform extremely well in this exposure condition, enduring 4,000 hours to date with no significant property changes. Unstabilized EVA and formulations without HALS type stabilizers degraded severely within the first 1,000 hours.

8. HALS stabilizers appear to be essential for the long life of EVA formulations.

9. Metal catalyzed degradation is the most severe form of accelerated aging discovered yet. The use of metal deactivators and silane treatment of the metal surface definitely extend the lifetime, however, it is strongly suggested that exposure to metallic copper be avoided , especially in high temperature applications.

   No reactions are observed with aluminum, 60/40 solder nickel, silver or titanium.

IV. ACCELERATED AGING AND LIFETIME STUDIES

A. Background

The candidate encapsulation materials being investigated in this project are intended for the construction of solar cell modules for terrestrial deployment and consequently must be capable of enduring the operating temperatures, insolation, precipitation and other elements of the outdoor exposure in the geographical region selected. Although the severity of these conditions may be fairly accurately gauged (climatic atlas, weather records, etc.) the lifetime and performance of individual materials or combinations of materials is not as easily assessed. The chemical pathways and rates at which materials age in outdoor exposures are very complex and predictive techniques often turn out to be inaccurate.

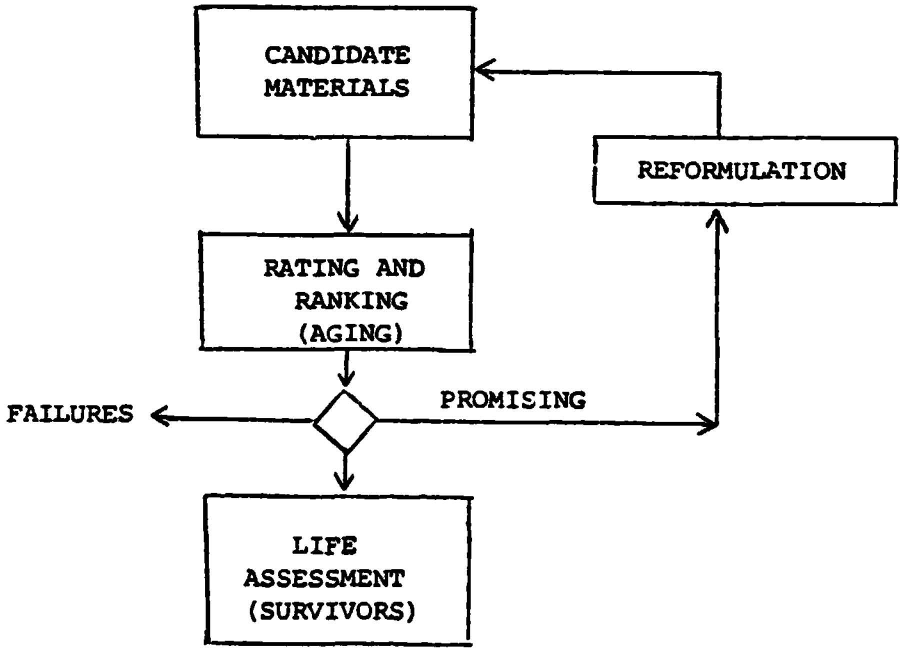
The degradation of polymeric materials in outdoor weathering is caused primarily by sunlight, especially the ultraviolet component. The deteriorating effect of light is usually enhanced by the presence of oxygen, moisture, heat, abrasion, etc. and is more accurately referred to as photooxidation, resulting from the combined effects of oxygen and sunlight. Sunlight at the earth's surface (filtered by the ozone layer) begins at 290 nm in the ultraviolet and continued through the visible ranges out to approximately 2,600 nm in the infrared. It is the ultraviolet portion of the spectrum (290 to 400 nm) that results in most of the photo-induced changes in polymeric materials.

Plastics vary considerably in their ultraviolet absorbing properties, but few are completely transparent in the 290 to 400 nm range. Once the radiant energy has been absorbed, the likelihood of chemical action will depend on the degree of absorption and the stability of the chemical bonds in the polymer. The induced chemical modifications are responsible for the deterioration of optical and mechanical properties and usually result in reductions of tensile strength, elongation and transparency. Specially formulated stabilizers are frequently used to interrupt this degradation chemistry and extend the service life of the polymer.

Accelerated tests are also used to assess long term aging effects and compare the effectiveness of stabilizers in providing improved protection against environmental deterioration. Typically, properties such as tensile strength, elongation at break, apparent modulus, resistance to flex cracking and other properties are measured on samples aged for known periods of time under specified conditions. These tests are useful for determining the relative stability of polymers and formulations, but correlation with actual service is infrequent.

In order to assess the relative stability of individual polymers and to determine the effectiveness of varying formulations, Springborn Laboratories is conducting a program of accelerated aging and life predictive strategies that should be useful for : (a) rating, ranking and reformulating candidate encapsulation materials, (b) generating practical data that relate to material performance under use conditions, and (c) generating data that may be useful in some type of predictive manner for life assessment.

The goals are being met by using the scheme presented in the following diagram:



This method is intended to serve as a multipurpose data source.

The stresses to which materials are exposed consist of the following, either singly or combined:

- (a) Thermal stress (heat aging)
  - in inert atmosphere
  - in air
- (b) Ultraviolet stress (UV exposure)
- (c) Hydrolytic stress (water exposure)
- (d) Catalytic stress (metal catalyzed oxidation)
- (e) Combined stresses (any of the above together)

The effects of these stresses on the candidate encapsulation materials is determined by measuring specific properties as a function of time. These properties were selected for their relevance to module service life and were chosen from four categories considered to be potentially life-limiting, as follows:

. Mechanical:	tensile strength, elongation, gel content, modulus
. Optical:	yellowing, haze, optical transmission from 0.4 to 1.1 microns
. Chemical:	loss of stabilizers, degradation, corrosion of interconnect metalization, metal catalyzed reactions, outgassing
. Dielectric:	field stress degradation, decay of breakdown strength, leak current, loss of electrical isolation

For the evaluation of individual materials and/or combinations of materials, a number of exposure conditions are being used, as follows:

1. Thermal Aging: This method employs the exposure of specimens to heat in an air oven. Atmospheres of air and nitrogen are both used.

2. RS/4 Exposure: This method uses the well accepted RS/4 sunlamp as a source of ultraviolet radiation and specimens are exposed on a rotating wheel beneath the lamp at a temperature of 50°C. Both dry and "wet" cycles (with water spray) are used.

3. <u>RS/4-85°C:</u> This is the same exposure as (2) except the temperature has been increased to include an additional stress.

4. <u>Controlled Environment Reactors</u>: These are devices designed and supplied by JPL and consist of chambers containing high power medium pressure mercury arc lamps a water spray nozzle.

5. <u>Metal Catalyzed Oxidation</u>: This condition is essentially thermal aging in the presence of metal (copper) which is known to rapidly accelerate degradation reactions.

6. <u>Outdoor Site Exposures</u>: Individual materials as well as whole modules have been exposed in Phoenix, Arizona and at Springborn's facilities at Enfield, Connecticut.

The details of these experiments and the results obtained have been documented in previous reports.(6) These methods have been useful for some comparisons of the relative durability of materials, but within particular limitations. These are:

(a) The use of light sources that do not duplicate the sun's spectrum and have an inconsistent output with respect to time (lamp darkening).

(b) Exceedingly long exposure times are required (sometimes several years) are required before the test specimen shows any sign of degradation.

(c) Unpredictable correlations between test exposure conditions and actual outdoor field exposures.

(d) Conditions that do result in relatively rapid degradation introduce overstresses that may now introduce chemical mechanisms that would not be found in field operations.

(e) In general, the conditions are too "artificial" and do not resemble outdoor environmental conditions.

B. Outdoor Photo Thermal Aging Reactors

Due to these objections, a different approach was considered to the aging of candidate encapsulation materials - the use of Outdoor Photo Thermal aging devices (OPTAR). These are devices recently constructed at Springborn Laboratories that constitute a new approach to accelerated weathering.(a)

The predominant cause of outdoor deterioration is photothermal aging; the combination of heat and ultraviolet light. In all the laboratory techniques devised to date, it is mainly the light that is increased (photoacceleration) through the use of arcs and discharge lamps. In the OPTAR reactors, natural sunlight is used as the light source and only the specimen temperature is increased. The OPTAR reactors consist of heated aluminum blocks surfaced with stainless steel and mounting hardware to hold the test specimens flush with the surface. The reactors are tilted at 45°C south and the device turns on at sunrise and off at sunset. Three temperatures have initially been selected: 70°C, 90°C, 105°C. This approach eliminates the difficulties associated with the irregular spectrum of artificial light sources, exposes the specimens to other environmental conditions such as rain and pollution, and additionally incorporates a dark cycle. The only acceleration, therefore, is in the temperature, all other environmental conditions being present in their natural occurrence and intensity. In summary, the OPTAR device is considered to have the following advantages:

(a) uses natural sunlight, therefore avoids the spectral distribution problems encountered with artificial light sources,

(b) uses temperature to accelerate the photothermal reactions and is easily controllable,

(c) includes dark-cycle reactions that are a natural part of field exposure,

(d) includes dew and rain water extraction effects,

(a) Subject of a paper to be published in fall of 1985.

(e) more closely resembles the environmental conditions experienced by solar modules,

(f) easily accomodates both discrete materials and entire modules, and

(g) may be set at any temperature desired for the purposes of varying the acceleration rate or extrapolating to lower temperatures.

Blueprints used in the construction of the OPTAR devices are included in the appendix, Figures 4 through 7.

a. Individual Formulation

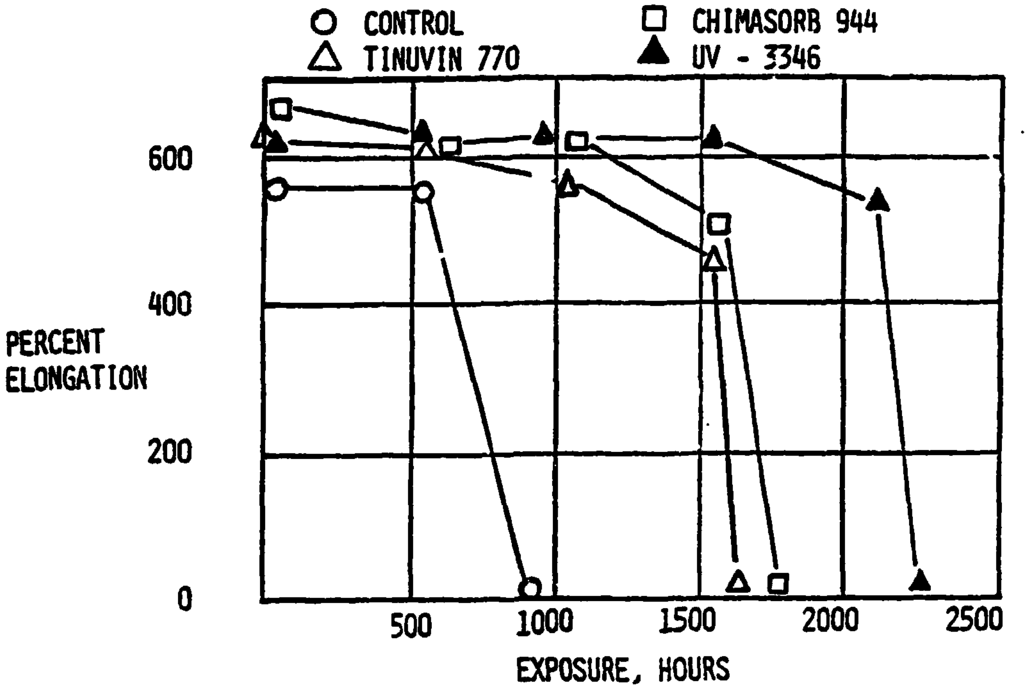
The outdoor photothermal aging reactors are operating very well and the temperature control at the surface is excellent. Of all the accelerated aging methods explored at Springborn Laboratories, this one results in degradation of candidate materials in the shortest time yet observed. At the 2,000 hour exposure point, all specimens of all candidate encapsulation materials have failed at the 105°C temperature, and at 90°C a number of materials have been terminated. At the 70°C condition, only one failure has been observed. The end of life for specimens on the OPTAR appears different than for failures under exposure to the RS/4 conditions, CERs or thermal aging. There is usually some decrease in the gel content and the formation of yellow coloration, however the polymer lose their physical properties by becoming "cheesy" and losing tensile strength, elongation and modulus. At termination, the resins usually have to be scraped off the surface of the OPTAR and no mechanical properties can be measured. This may be the case even when the gel content is still high. This effect is sometimes observed in polymers in which there are simultaneous chain scission and crosslinking reactions occurring. The effect is that the gel content remains high from crosslinking reactions, but the physical properties resulting from high molecular weight chains is lost. It is not known yet if this is the case with the OPT specimens. Summarized data for the OPTAR specimens is shown in the following table.

Individual Formulations: OPTAR Exposure

Material	Performance	Temperature (°C)	Time Hours
EVA 16718B (TBEC, UV2098, no Tinuvin-770)	Degraded, "cheesy"	70	2,000
EVA A9918	Degraded, "cheesy"	90	2,000
EVA 16718A (TBEC, UV2098, Tinuvin-770)	Degraded, "cheesy"	90	1,000
EVA 16718B (no Tinuvin-770)	Degraded	90	1,000
EMA 15257	Yellow, "cheesy"	90	2,000
PU Z-2591	Very dark color, very sticky, but OK mechanical properties. Cannot be handled.	90	2,000
EVA A9918	"Cheesy" with some flow, very tacky	105	2,000
EVA 16718B (no Tinuvin-770)	"Chessy" with flow, no color, cannot be tested, tacky.	105	1,000
EMA 15257	Yellow color, "cheesy"	105	2,000
PU Z-2591	Dark color, very tacky, cannot be tested.	105	2,000

As this table shows, the first useful result of the OPTAR devices are that materials may be brought to degradation in relatively short periods of time under conditions similar to those that might be experienced in worst-case field conditions. This permits the development and comparative performance testing of formulations in reasonable short periods of time. An example is the comparative evaluation of HALS stabilizers for the light stabilization of EVA. Test specimens were prepared from crosslinked Elvax 150 using 0.1% of a commercially available HALS compound as the only stabilizer. These specimens were then exposed on the OPTAR at 90°C and the percent ultimate elongation measured as a function of time. The results are graphed as follows:

OPTAR Evaluation: HALS Stabilizers



These results indicate that Cyasorb UV-3346 (American Cyanamide) is clearly a better choice of HALS stabilizer for use in EVA.

Once the OPTARS were found to be useful for the accelerated aging of polymers in reasonably short periods of time, experiments were conducted to determine if some type of predictive methodology could be applied.

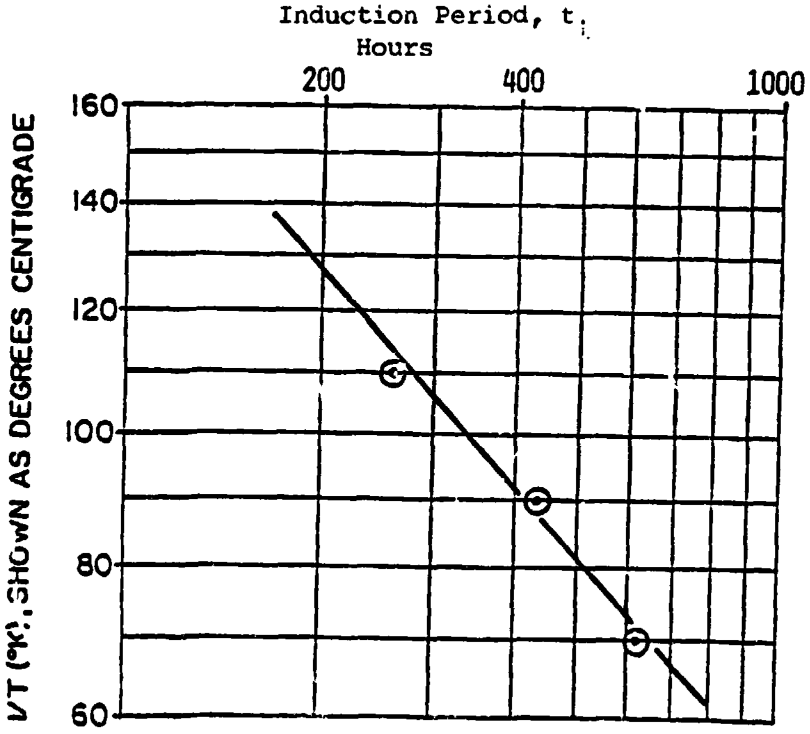
b. Predictive Moldeling

A number of approaches to data modeling may be considered, the simplest being first order behavior in which the log of the property being measured is linear over time. This relationship may be used easily for life prediction, especially when the reaction rate is proportional to the temperature (Arrhenius relationship). Polymer degradation is frequently a complex relationship of many competing chemical reactions, however, and may shift dramatically with subtle changes in temperature, light intensity, additives, etc. The behavior most frequently observed is the "induction period" type in which the degradation rate suddenly changes and the property vs. time curve shows a sharp downward trend.

The time to the onset of this change is the induction period and is often used to measure the efficiency of antioxidants, (isothermal DTA). This approach was used in modeling the OPTAR conditions with the assumption that the mechanism of degradation is consistent over the 70°C to 105°C range.

Polypropylene was selected as a model polymer for this test due to the fact that its induction period, t_i, is sharp and easily measured. This is shown as a sudden drop in the elongation at break. Tensile bars of unstabilized compression molded polypropylene were placed on the OPTAR devices at the three temperatures and the log of the induction period measured as a function of reciprocal temperature. The following graph shows that the relationship is linear and a close approximation to the Arrhenius function exists.

OPTAR Degradation of Polypropylene



This data is extremely encouraging and suggests that wherever an induction period can be identified, the possibility for predictive modeling exists. Statistical extrapolation through these points to a mean ambient temperature of 20°C gives a predicted life (induction period) of 2,300 hours (three months), which is known to be the actual life of polypropylene in outdoor aging at the same exposure site. This fact adds to the credibility of this method, however more data must be taken (and with different polymers) to thoroughly validate this approach.

c. Module Exposure

If this model can be applied to EVA formulations, or other components of solar module encapsulation, then life time prediction may become possible by extrapolating the curve to lower temperatures and long periods of time. It will also give an indication of the upper level service temperature that can be tolerated for a thirty year module life. The main intention of the OPT devises was to age modules, however. Trial modules were constructed and deployed on the OPTARs in order to determine how material might behave in the context of a module.

Four types of "mini" modules were prepared of 5"x8.25" size, each containing two interconnected [illegible]0 mm diameter solar cells (Solar Power Corporation, Woburn, MA). Each module consisted of the following components; (a) glass primed with 11861 primer, (b) the EVA formulation, (c) the cell pair, (d) the second layer of EVA, and (e) a back cover film of white Tedlar (200BS30WH).

The modules were prepared by the usual vacuum bag lamination technique coated with a layer of primer (68040) and four EVA formulations prepared, each test a formulation variable, as follows:

Module Formulations

Module Number	Pottant Formulation No.	Formulations
16747-1	A9918	Standard Formulation: (Lupersol 101, UV-531,Tinuvin 770)
16747-2	16718A	Advanced EVA Formulation: (TBEC, UV-2098, Tinuvin 770)
16747-3	16717	Advanced EMA Formulation: (TBEC, UV-2098, Tinuvin 770)
16747-4	14747	Experimental EVA Formulation: (Lupersol 101, UV-2098, Tinuvin 770)

In addition, each module was prepared with a 1" x 0.75" piece of untreated copper mesh encapsulated in the pottant to determine the severity of copper activation effects. The modules were evaluated by visual inspection. Tables of results appear in the appendix, pages A-1 through A-12.

The following table gives the general results of module performance on OPTAR reactors after 5000 hours of exposure.

OPTAR Exposure: Modules

Number	Pottant	Component	70°C	90°C	105°C
16147-1	EVA A9918	Pottant	1	A2	A4
		Copper	A2	A2, E3	A5, E5
		Glass	1	1	B
		Metalization	1	C2	1
16147-2	EVA 16718A	Pottant	1	1	A2
		Copper	1	1	A4
		Glass	1	1	B
		Metalization	1	C2	1
16718-3	EMA 16717	Pottant	1	1	A2
		Copper	1	1	A4
		Glass	1	1	B
		Metalization	1	1	1
16718-3	EVA 14747	Pottant	1	A3	A4
		Copper	1	A2	A3
		Glass	B	B	B
		Metalization	1	C3	C3

A = discoloration
B = broken/fractured
C = corrosion (metalization)
D = delamination
E = flow/melt

1 = no change
2 = slight change
3 = noticeable
4 = moderate
5 = severe

In all cases, the first change to be noticed was slight discoloration in the vicinity of the copper mesh. This was also anticipated to be the first source of degradation, however at 70°C it is barely noticeable after 5,000 hours and is only found in one module (EVA A9918). Apart from this effect, there are no other changes that can be observed in any of the modules at the 70°C/5000 hour condition.

At 90°C the copper discoloration became noticeable in two modules (both using Lupersol-101 as the curing agent), and at 105°C was dramatically visible in all four. In addition to the strong orange/brown color around the copper mesh, signs of flow of the pottant could also be found, especially in the module using EVA A-9918. In the 90°C/5000 hour condition, a few other effects became noticeable. Some discoloration (yellowing) of the pottant was found in the module prepared with EVA 9918 and EVA 14747. Both of these formulations have the similarity of being cured with Lupersol-101, which suggests that this curing agent might result in slightly less photostable compositions than the Lupersol -TBEC used in the other two compositions.

Also at 90°C, small amounts of corrosion (presumably) around the interconnects, could be noticed in the form of slight haze and yellowing. These areas are very small, however, and do not appear to threaten the electrical functioning of the module. Interestingly, these "corrosion" effects were not noticed in the 105°C exposure.

At the 105°C/5000 hour test point, degradative effects were now quite noticeable. The glass outer covers all showed meandering cracks due to thermal shock, the copper catalyzed degradation of the pottant was striking and all the pottants showed some degree of discoloration.

No broken cells, or change in the electrical functions, was found in any of the cells. Of the four formulations tested, the least amount of change was found in the module fabricated with EVA formula 16718A. This is an experimental "advanced" formulation cured with Lupersol-TBEC and containing the co-reacted UV-2098 ultraviolet screener and Tinuvin-770 HALS compound. These experiments have proven to be very useful in,

(1) demonstrating the performance enhancement of advanced formulations, and (2) showing that the encapsulation components are much more stable when incorporated into a module than when exposed alone. This is the purpose of encapsulation; to provide a combination of materials that mutually enhance each others service life in order to maximize module performance. These experimental modules will continue under OPTAR exposure until total loss of electrical output is observed.

V. HARDBOARD SUBSTRATES

At the beginning of the solar cell encapsulation program, the need for a rigid load bearing support for the cells became obvious and two basic "styles" of solar cell encapsulation became apparent: superstrate and substrate. The superstrate design supports the cells on the sunlit side and the substrate style supports the cells from the underside. A study then followed to explore the economic merits of both styles in order to discover the most cost-effective design. This study commenced with a first-cut engineering analysis to determine the cost and mechanical performance of candidate substrate materials. The working model was considered to be of 1.2 meters length, 0.4 meters width with requirement of having a center-point deflection of no more than 6 mm at a 50 lb/ft^2 wind loading. This criteria permitted a stress-strain equation to be calculated in which the thickness and flexural modulus of candidate materials could be substituted. Published values of modulus, density and cost per pound then permitted an extensive survey of candidates to be compared.(2) This work was further extended at JPL to the creation of "Master curves" that serve as design tools for the calculation of solar cell stresses based on any combination of structural panel parameters, pottant properties, thermal stresses, wind loadings and combined stresses.(3)

The results of these surveys suggest that the load bearing element, either substrate or superstrate will be the most expensive single component in the encapsulation package. Given the overall encapsulation cost goal of \$14.00/m^2 (1980 dollars), the load bearing element may amount to as much as 50% of the cost, or up to \$7.00/m^2.

Surveys have identified potential construction materials on the basis of the flexural strength required to meet the load deflection specifications and the cost of the material at the required thickness. The lowest costing materials identified to date as are follows:

Module Substrates

Candidate Material	Estimated Cost $/ft^2$	Estimated Cost $/m^2$
Hardboards (Masonite, "Super-Dorlux", Ukiah Standard Hardboard)	0.14	1.52
Strandboard (Potlatch-under development)	0.17	1.80
Glass-reinforced concrete (MBA Associates)	0.60	6.50
Mild steel (28 gauge) (base cost approx. 1¢ per sq. ft. per mil of thickness)	0.25	2.70

Although these products represent the lowest costing construction materials suitable for the application, they all have weathering deficiencies that must be compensated before they are suitable candidates. Coatings for the environmental protection of mild steel have been evaluated in previous reports.(5)

Hardboards; Coatings

Hardboard has been found to have the best cost/performance ratio of any structural material investigated as a candidate substrate to date. Mechanical analysis shows that 1/4" hardboard at cost in the range of $0.18 to $0.20 per square foot offers the highest flexural strength at the lowest possible cost. Only a single reinforcing rib in the longitudinal direction is requried for the fabrication of a 2' x 4' substrate module. The difficulty with the use of hardboard is that an additional cost component must be included for some type of protective treatment. Hardboards are very hydroscopic materials, with coefficients of hydroscopic expansion in the order of two magnitudes larger than the coefficient of thermal expansion(a). In order for these materials to be used effectively,

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(a) Coefficient of hydroscopic expansion measured to be approx. 5×10^{-5} in/in/% RH.

the dimensional changes that occur with the uptake and loss of water must be eliminated. There are no inexpensive chemical treatments that can be used to prevent the hardboard from being hygroscopic and there do not appear to be any occlusive paints that are capable of preventing the intrusion of water, as either liquid or vapor. The proposed solution to this problem is the application of some type of film material that is either totally occlusive, such as a metal foil, or partially occlusive such as a polymer film. The protective film need not be totally occlusive as long as the water vapor permeation rate is low enough to damp out the effects of varying humidity in the environment.

Due to the tendency for hardboards to dessicate very rapidly under these conditions, the protective films must be applied without the vacuum lamination process. It is necessary to "seal in" an amount of water equal to the seasonal mean humidity so that there is no gradual trend for the hardboard to change its dimension through gradual gain or loss of water. Solar cell fabrication using these materials necessitates a "split process" in which the unmounted "module" of encapsulated solar cells is prepared in a vacuum process and then laminated to the hardboard under ambient temperature and pressure conditions in a subsequent step. This prevents exposure of the hardboard dessicating conditions. The encapsulated solar cell assembly constitutes the protective film on the top side and therefore only one other is needed for the underside.

Selecting the costing-out candidate protective films for this application is not too difficult, however, the major concern has been the cost of the process in which the films are attached to the hardboard to produce a "module ready" substrate. This has required careful consideration of the types of adhesives to be used, application machinery, cure cycles, raw materials handling, factory operation, equipment costs, depreciation, etc.

The attached pages in the appendix provide the detail for a "typical" manufacturing operation in which a flexible laminate of encapsulated solar cells forms one of the protective water vapor barriers for the hardboard and an occlusive film is used to cover the opposite side. Due to the fact that the attachment of the cell string to the load bearing member occurs in two states, we are using the term "split process" to designate this type of fabrication. The appendixed pages give the manufacturing and cost details considered in this process. Pages A14 through A15 gives the sequence of manufacturing steps required; page A16 shows the Production Flow Chart, and pages A17 and A18 give the resulting cost estimates in 1984 and 1980 dollars, respectively. The supporting calculations used in the preparation of these estimates have been published in a previous document.

The results of this analysis indicate that the process only cost for fabrication of PV modules by the "split process" using hardboards is about \$2.46/m^2 in 1980 dollars, and about \$3.19/m^2 in 1984 dollars. This is process cost and does not include any raw materials such as adhesives, films, or solar cells. This cost is additional to the cost of preparing modules by the vacuum bag process in a single step in which glass is usually used, and a completed module results. Soda-lime glass is currently about \$9.70 per square meter. The split process would employ the same vacuum bag cycle for solar cell encapsulation at \$6.08/m^2,(7) and add about \$3.19/m^2 for the split process, about \$1.80/m^2 for the hardboard and (for example) \$1.10 per square meter for adhesives and the back cover film for a total of \$12.17/m^2 total process cost. This would constitute a savings of \$3.61/m^2 over the cost of a glass superstrate module costing \$15.78/m^2. This potential cost reduction indicates the split process idea is worthy of further investigation and should now be costed out, including raw materials for a more accurate comparison.

the dimensional changes that occur with the uptake and loss of water must be eliminated. There are no inexpensive chemical treatments that can be used to prevent the hardboard from being hygroscopic and there do not appear to be any occlusive paints that are capable of preventing the intrusion of water, as either liquid or vapor. The proposed solution to this problem is the application of some type of film material that is either totally occlusive, such as a metal foil, or partially occlusive such as a polymer film. The protective film need not be totally occlusive as long as the water vapor permeation rate is low enough to damp out the effects of varying humidity in the environment.

Due to the tendency for hardboards to dessicate very rapidly under these conditions, the protective films must be applied without the vacuum lamination process. It is necessary to "seal in" an amount of water equal to the seasonal mean humidity so that there is no gradual trend for the hardboard to change its dimension through gradual gain or loss of water. Solar cell fabrication using these materials necessitates a "split process" in which the unmounted "module" of encapsulated solar cells is prepared in a vacuum process and then laminated to the hardboard under ambient temperature and pressure conditions in a subsequent step. This prevents exposure of the hardboard dessicating conditions. The encapsulated solar cell assembly constitutes the protective film on the top side and therefore only one other is needed for the underside.

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VI. ANTI-SOILING TREATMENTS

The power output of photovoltaic modules is reduced by the accumulation of soil on the surface. The loss is due to shadowing of the cell, and losses of several percent may result. To minimize performance losses caused by soiling, photovoltaic modules not only should be deployed in low-soiling geographical areas, but also should have surfaces or surfacing materials with low affinity for soil retention, maximum susceptibility to natural removal by winds, rain, and snow; and should be readily cleanable by simple and inexpensive maintenance cleaning techniques.

The theoretical aspects of soiling have been addressed recently in documents by the Jet Propulsion Laboratory.(4) The basic findings of these studies show that the rate of soil accumulation in the same geographical area is material independent and that rainfall functions as a natural cleaning agent. The effectiveness of the cleaning effect of the rain is material dependent, however.

Based on the postulated mechanisms for soil retention on surfaces, certain characteristics of low-soiling surfaces may be assumed. They are, (a) hard, (b) smooth, (c) low in surface energy, (d) chemically clean of water soluble salts, and (e) chemically clean of sticky materials. It is possible that cost effective coatings having these properties may exist and be applied to solar module surfaces. This may result in low maintenance costs and preserve the effective generation of power from these modules.

Over the past few years Springborn Laboratories has evaluated the effectiveness of low surface energy treatments applied to candidate outer cover materials for use in solar modules. These candidate materials currently consist of low-iron glass, Tedlar fluorocarbon film (DuPont) and a biaxially oriented acrylic film (Acrylar; product X-22417, 3M Corp.). These materials are all relatively hard, smooth and free of water soluble residues and experiments were conducted to determine if an improvement in soiling resistance could be obtained by the application of low surface energy treatments.

A survey of coating materials showed that very few commercial materials exist that could be useful for this purpose and that some experimental compounds had to be synthesized.

The anti-soiling experiments initially used seven treatments that included fluorocarbons, acrylics and silicone based materials. After the first year of exposure it became clear that a number of candidates were ineffective and were consequently discontinued. Four treatments were continued in order to assess the long term performance in an outdoor soiling environment, as follows:

1. L-1668, an experimental fluorochemical silane produced by 3M Corporation that is used to impart water and oil repellency to glass surfaces. This material is not yet commercial.
2. L-1668 following treatment of the surface with ozone activation (for the organic films only).
3. Dow Corning E-3820-103B, and experimental treatment consisting of perfluorodecanoic acid coupled to a silane (Z-6020). This compound is not commercially available, but is easily prepared.
4. The E-3820-103B following surface treatment with ozone to create active sites on the organic polymer films.

These candidates consist of two surface coatings, but four treatments. Each coating is applied with and without surface treatment with ozone in order to activate bonding chemistry at the surface and enhance adhesion. No ozone treatment is used with the glass because surface activation is not required in this case.

These coatings/treatments were applied to each of the three candidate outer surfaces using the recommended application technique. The organic film materials, Tedlar and Acrylar were supported by a piece of glass on the underside, and attached with a colorless and ultraviolet stable pressure sensitive adhesive. The completed test coupons were then mounted in outdoor racks on the roof of Springborn Laboratories' facilities in Enfield, Connecticut. Evaluation is performed monthly and a record of rainfall is also kept in order to correlate soiling effects with precipitation.

The degree of soiling on the completed specimens was measured by power transmission using a specially designed standard cell device. This instrument measures the drop in short circuit current, I_{sc}, when the soiling specimen is placed between the standard cell and the light source. This value is then compared to control and the percent decrease calculated.

The results of 38 months of outdoor exposure are shown graphically in figures 8 through 10 of the appendix. Only the best treatment and the control values are plotted, for clarity. Observation of the data reveals that a fluctuating, but generally increasing loss in power is found for all specimens. The degree of loss varies according to the type of surface treatment and the particular month of exposure.

Sunadex glass, and the treatments applied to it, gave specimens with the best overall inherent soil resistance. The control,and most of the coated specimens, followed the same pattern of rising and falling simulataneously throughout the exposure period in agreement with the amount of rainfall. The winter months showed a dramatic decrease in power in all cases. A constant differential was found between the control measurements and the two most effective coatings, as may be seen in the figures.

The best overall coating is found to be the compound designated E-3820 and gives reductions in I_{sc} that are .5 to 1% higher than the untreated control specimen. The estimated average power gain resulting from the self-cleaning property of this coating is in the order of 1% over the thirty-eight month period.

The Acrylar acrylic film formulations soiled much more severely than the Sunadex glass specimens. All the specimens steadily lost power throughout the exposure period, however almost all of the treatments had a beneficial effect. The uncoated control specimens soiled very badly and, at one point (10th month), dropped to a low -10.8% power loss. After the twelfth month, the control value returned to a -7.8% power loss, with most of the treated specimens showing a 4 to 5% loss. The effectiveness of the coatings/treatments may be compared by

Anti-soiling Treatments: Acrylar

Coating Treatment	38 Month Loss in I_{sc}
Control, none	-8.7%
L-1668	-5.8%
Ozone, L-1668	-6.3%
E-3820	-5.8%
Ozone, E-3820	-1.5%

As was found with the Sunadex glass specimens, the treatment based on E-3820 appears to be the best, but ozone activation of the surface is required in order to get the compound to bond and form a durable coating. The use of this treatment on Acrylar resulted in a spectacular improvement in short circuit current, as may be seen in Figure 8 (appendix). Based on the difference between the control and treated values, the estimated average improvement in power is in the order of 3.9%.

The third, and last, candidate outer surface to be investigated was Tedlar (100BG30UT), a transparent UV absorbing film of poly(vinyl fluoride) manufactured by DuPont. As with the Acrylar film, this material was mounted on glass squares with a pressure sensitive acrylic adhesive and deployed with the usual series of coatings/treatments. The overall performance of these specimens was better than the Acrylar, but worse than the Sunadex glass. The control degraded steadily in power throughput reaching almost 9% loss in the tenth month and the slowly recovered to a 4% to 6% loss that varied over the exposure period.

All the coatings/treatments applied to the Tedlar were more efficient in retarding soil accumulation than the control. As with the previous two candidates, the fluorosilane treatments gave the best performance, the best , again, being the E-3820 compound, which consistantly gave a 4% to 5% improvement in performance over the exposure period.

After 38 months of exposure the I_{sc} values were found to be:

Anti-soiling Treatments: Tedlar

Coating Treatment	38 Month Loss in I_{sc}
Control, none	-4.8%
L-1668	-5.0%
Ozone, L-1668	-3.6%
E-3820	-2.1%
Ozone, E-3820	-3.9%

As previously, the E-3820 formulation is the most effective, however the ozone treatment does not appear to be necessary. Although the treatments still appear to be effective after the three year exposure time some weathering effects.

All the specimens retrieved from the outdoor aging racks were found to have lost a good deal of their water repellency. When sprayed with a jet of distilled water, all the exposed surfaces showed wetting, even the Sunadex/ E-3820 specimen. In contrast, freshly treated surfaces are conspiciously water repellent and water droplets bead up instantly. An attempt was made to determine the surface energy of the exposed specimens by the contact angle technique, employing liquids of varying surface tension, however difficulties were encountered with the measurements and no meaningful data resulted.

In summary, low surface energy treatments based on fluorosilane chemistry appear to be effective in retarding the accumulation of dirt on the candidate outer surfaces of interest. The most effective soil retardant treatments identified to date are: for Sunadex glass, E-3820; for Acrylar, ozone activation followed by E-3820; and for Tedlar, treatment with E-3820 but with no ozone activation. After three years of outdoor exposure, the best treatments still gave improvements of 2-1/2% to 4% in light throughput measured with a standard cell and light source. The removal of accumulated soil correlated well with rainfall, but not with precipitation as snowfall.

The obvious visual difference in the wetting of exposed versus freshly prepared specimens indicates that the low surface tension treatments are prone to either chemical degradation or physical loss and may have to be replenished on a periodic basis. A maintenance schedule needs to be determined based on the cost of produced power gained by employing the coatings versus the cost of routine maintenance required for cleaning and recoating the surfaces. This study will be performed in the proceeding months of this program and the cost effectiveness of these approaches will be determined.

VII. FUTURE WORK

In the next year's work, Springborn Laboratories will continue with some of the technical topics included in this report and will also introduce some new areas of study relating to module performance. The research topics will include the following:

1. Outdoor Photo Thermal Aging Reactors(OPTAR)

   Aging experiments will continue with these devices with the inclusion of whole modules, advanced pottant formulations, optical test specimens, dielectric test specimens and more calibration materials. Experiments will be conducted to model the kinetics of degradation and enhance the predictive capabilities of this approach.

2. Advnaced Stabilizers:

   Experiments have shown that some new ultraviolet stabilizers recently introduced on the market offer enhancement in performance. These compounds, being co-reactive ultraviolet absorbers and high molecular weight HALS compounds, will be used for the preparation of technically advanced grades of EVA and will be evaluated for suitability in PV module applications.

3. Dielectric Testing:

   One of the performance criteria for pottants is that they provide electrical isolation between the electrically conductive components of the module. The dielectric strength of the pottant materials appears to be more than adequate for this application, however it is not currently known if this insulation strength changes or degrades with environmental exposure. A series of dielectric property test experiments have been started that assess the "intrinsic dielectric strength of the candidate pottant (in DC mode) and can subsequently be used to determine if this value changes with time. Test specimens from accelerated aging conditions will be used to examine the effects of aging on this important property.

4. Adhesion:

There are two topics of interest in adhesion studies currently; the narrowing of the list of candidate formulations, and the lifetime and performance evaluation. Previous experimental work has resulted in many primers for many interfaces. In the future, development efforts will be directed towards the formulation of three "universal" primers. These primers are intended for use with the three general interfaces that are found in PV modules; (a) polymer-polymer, (b) polymer-metal, and (c) polymer-inorganic. These formulations will be developed and evaluated with the assistance of Dow Corning Chemical Co. New methods for predicting the service life of primed interfaces are being explored using spectroscopic techniques such as DRIFT, RAIR and elipsometry. Springborn will participate in programs at the University of Cincinnati and Case Western Reserve in an attempt to measure the chemical and mechanical aspects of degradation at the interface. Kinetic analysis will also, hopefully, result that will permit service life estimations to be calculated.

5. Anti-Soiling Treatments:

The soiling specimens currently under exposure will continue until significant loss of the surface activity is observed. In addition, two or three new candidates will be started based on some advanced concepts in surface modification. A cost analysis and maintenance schedule is also planned to demonstrate the cost effectiveness of these materials.

6. Flammability:

The flammability of PV modules is an area of growing concern. Although modules contain only small amounts of combustible materials, it has been shown that they have the potential to spread fire under certain circumstances. Three methods will be explored in order to reduce this risk. They are: (a) reduction of the amount of combustible material in the module, (b) the use of fire retardant additives to the pottant, and (c) the use of high strength back cover films to inhibit the release of burning gasses. Evaluation of these approaches will be accomplished with the use of a special high temperature burst cell, small scale burning brand tests, and full scale "burns".

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3. E. F. Cuddihy, "Development of Reduced Variable Master Curves for Estimating Tensile Stresses of Encapsulated Solar Cells Caused by Module Deflection cr Thermal Expansion", LSA Project Task Report 5101-182, October 1981.

4. E. F. Cuddihy, P. B. Willis,"Antisoiling Technology: Theories of Surface Soiling and Performance of Antisoiling Coatings", LSA Project Task Report, November 1984.

5. P. B. Willis, B. Baum, "Investigation of Test Methods, Material Properties and Processes for Solar Cell Encapsulants", Springborn Laboratories, Inc., JPL Contract 954527 Annual Report, July 1982.

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7. P. B. Willis, B. Baum, "Investigation of Test Methods, Material Properties and Processes for Solar Cell Encapsulants", JPL/DOE 954527, Annual Report, July 1980.

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1. Willis, P., Baum, B. and White, R., Encapsulation Task 2nd Annual Report, ERDA/JPL-954527, Springborn Laboratories, Inc., July 1978.

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7. P. B. Willis, B. Baum, "Investigation of Test Methods, Material Properties and Processes for Solar Cell Encapsulants", JPL/DOE 954527, Annual Report, July 1980.

APPENDIX

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MODULE EXPOSURE

Notebook Number: 16747-1 Test Site: Enfield, Ct.

Exposure Condition: OPT-70° C Size: 5 1/2" x 9" 2-cell

Construction: Glass (11861)/ EVA 9918 /Cells(11861) /EVA/Tedlar 200BS30WH - (68040)

Test	Exposure, Hours	1,000	2,000	3,000	4,000	5,000
	Test Date 11/2/83	12/14/84	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches	8.35	1.8	3.93	3.60	
Cells	Condition	1				
	Voltage, V_{oc}					
	Current, I_{sc}					
Metals	Cell Metalization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	at edge:	1	1	1	1	1
	internally:	1	1	1	1	1
Encapsulation	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
	Sealant					
	Gasket					
	Pottant	1	1	1	1	1
	Pottant + Copper	1	1	1	1	A2
	Pottant Delamination:	1	1	1	1	1
	Cells + Metallization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
Notes						

A = Discoloration
B = Broken/fractured
C = Corrosion
D = Delamination
E = Flow/melt

1 = No change
2 = Slight Change
3 = Noticable
4 = Moderate
5 = Severe

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MODULE EXPOSURE

Notebook Number: 16747-2 Test Site: Enfield, Ct.

Exposure Condition: OPT-70°C Size: 5 1/2" x 9" 2-cell

Construction: Glass(11861)/EVA 16718A/cells(11861)/EVA/Tedlar 200BS30WH-
(68040) (TBEC/2098/770)

Test	Exposure, Hours		1,000	2,000	3,000	4,000	5,000
	Test Date	11/2/83	12/14/83	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches		8.35	1.8	3.93	3.60	
Cells	Condition		1	1	1	1	1
	Voltage, V_{oc}						
	Current, I_{sc}						
Metals	Cell Metalization		1	1	1	1	1
	Interconnects		1	1	1	1	1
		at edge:	1	1	1	1	1
		internally:	1	1	1	1	1
Encapsulation	Outer Cover		1	1	1	1	1
	Back Cover		1	1	1	1	1
	Sealant						
	Gasket						
	Pottant		1	1	1	1	1
	Pottant + Copper		1	1	1	1	1
	Pottant Delamination:		1	1	1	1	1
		Cells + Metallization	1	1	1	1	1
		Interconnects	1	1	1	1	1
		Outer Cover	1	1	1	1	1
		Back Cover	1	1	1	1	1
Notes							

A = Discoloration
B = Broken/fractured
C = Corrosion
D = Delamination
E = Flow/melt

1 = No change
2 = Slight Change
3 = Noticable
4 = Moderate
5 = Severe

MODULE EXPOSURE

Notebook Number: 16747-3
Test Site: Enfield, Ct.
Exposure Condition: OPT-70° C
Size: 5 1/2" x 9" 2-cell

Construction: Glass(11861) / EMA 16717 /Cells(11861)/Tedlar200BS30WH(68040)

Test	Exposure, Hours	1,000	2,000	3,000	4,000	5,000
	Test Date 11/2/83	12/14/83	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches	8.35	1.8	3.93	3.60	
Cells	Condition	1	1	1	1	1
	Voltage, V_{oc}					
	Current, I_{sc}					
Metals	Cell Metalization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	at edge:	1	1	1	1	1
	internally:	1	1	1	1	1
Encapsulation	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
	Sealant					
	Gasket					
	Pottant	1	1	1	1	1
	Pottant + Copper	1	1	1	1	1
	Pottant Delamination:	1	1	1	1	1
	Cells + Metallization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
Notes						

A = Discoloration
B = Broken/fractured
C = Corrosion
D = Delamination
E = Flow/melt

1 = No change
2 = Slight Change
3 = Noticable
4 = Moderate
5 = Severe

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MODULE EXPOSURE

Notebook Number: 16747-4
Test Site: Enfield, Ct.
Exposure Condition: OPT-70° C
Size: 5 1/2" x 9" 2-cell

Construction: Glass(11861) / EVA 14747 /cells(11861) / Tedlar200BS30WH(68040)

Test	Exposure, Hours	1,000	2,000	3,000	4,000	5,000
	Test Date 11/2/83	12/14/84	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches	8.35	1.8	3.93	3.60	
Cells	Condition	1	1	1	1	
	Voltage, V_{oc}					
	Current, I_{sc}					
Metals	Cell Metalization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	at edge:	1	1	1	1	1
	internally:	1	1	1	1	1
Encapsulation	Outer Cover	B	B	B	B	B
	Back Cover	1	1	1	1	1
	Sealant					
	Gasket					
	Pottant	1	1	1	1	1
	Pottant + Copper	1	1	1	1	1
	Pottant Delamination:	1	1	1	1	1
	Cells + Metallization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
Notes		Glass cracked				

A = Discoloration
B = Broken/fractured
C = Corrosion
D = Delamination
E = Flow/melt

1 = No change
2 = Slight Change
3 = Noticable
4 = Moderate
5 = Severe

MODULE EXPOSURE

Notebook Number: 16747-1 Test Site: Enfield, Ct.

Exposure Condition: OPT-90°C Size: 5 1/2" x 9" 2-cell

Construction: Glass (11861)/ EVA 9918 /Cells(11861) /EVA/Tedlar 200BS30WH - (68040)

Test	Exposure, Hours	1,000	2,000	3,000	4,000	5,000
	Test Date 11/2/83	12/14/83	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches	8.35	1.8	3.93	3.60	
Cells	Condition	1	1	1	2	2
	Voltage, V_{oc}					
	Current, I_{sc}					
Metals	Cell Metalization	1	1	1	1	1
	Interconnects	2	2	2	2	2
	at edge:	1	1	1	1	1
	internally:	C2	C2	C2	C2	C2
Encapsulation	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
	Sealant					
	Gasket					
	Pottant	1	1	1	1	A2
	Pottant - Copper	A2	A2 E2	E3	E3	A2 E3
	Pottant Delamination:	1	1	1	1	1
	Cells + Metallization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
Notes		Slight color near copper		Copper mesh- some bubbles, no color		

A = Discoloration
B = Broken/fractured
C = Corrosion
D = Delamination
E = Flow/melt

1 = No change
2 = Slight Change
3 = Noticable
4 = Moderate
5 = Severe

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MODULE EXPOSURE

Notebook Number: 16747-2 Test Site: Enfield, Ct.

Exposure Condition: OPT-90°C Size: 5 1/2" x 9" 2-cell

Construction: Glass(11861)/EVA 16718A/cells(11861)/EVA/Tedlar 200BS30WH-(68040)

Test	Exposure, Hours	1,000	2,000	3,000	4,000	5,000
	Test Date 11/2/83	12/14/84	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches	8.35	1.8	3.93	3.60	
Cells	Condition	1	1	1	1	1
	Voltage, V_{oc}					
	Current, I_{sc}					
Metals	Cell Metalization	1	1	1	1	1
	Interconnects	2	2	A2	A2	A2
	at edge:	1	1	1	1	1
	internally:	C2	C2	C2	C2	C2
Encapsulation	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
	Sealant					
	Gasket					
	Pottant	1	1	1	1	1
	Pottant + Copper	1	1	1	1	1
	Pottant Delamination:	1	1	1	1	1
	Cells + Metallization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
Notes						

A	= Discoloration	1	= No Change
B	= Broken/fractured	2	= Slight Change
C	= Corrosion	3	= Noticable
D	= Delamination	4	= Moderate
E	= Flow/melt	5	= Severe

MODULE EXPOSURE

Notebook Number: 16747-3 Test Site: Enfield, Ct.
Exposure Condition: OPT-90°C Size: 5 1/2" x 9" 2-cell

Construction: Glass(11861) /EMA 16717 /Cells(11861)/Tedlar200BS30WH(68040)

Test	Exposure, Hours		1,000	2,000	3,000	4,000	5,000
	Test Date 11/2/83		12/14/83	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches		8.35	1.8	3.93	3.60	
Cells	Condition		1	1	1	1	
	Voltage, V_{oc}						
	Current, I_{sc}						
Metals	Cell Metalization		1	1	1	1	1
	Interconnects		1	1	1	1	1
		at edge:	1	1	1	1	1
		internally:	1	1	1	1	1
Encapsulation	Outer Cover		1	1	1	1	1
	Back Cover		1	1	1	1	1
	Sealant						
	Gasket						
	Pottant		1	1	1	1	1
	Pottant + Copper		1	1	1	1	1
	Pottant Delamination:		1	1	1	1	1
		Cells + Metallization	1	1	1	1	1
		Interconnects	1	1	1	1	1
		Outer Cover	1	1	1	1	1
		Back Cover	1	1	1	1	1
Notes							

A	= Discoloration	1	= No change
B	= Broken/fractured	2	= Slight Change
C	= Corrosion	3	= Noticable
D	= Delamination	4	= Moderate
E	= Flow/melt	5	= Severe

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MODULE EXPOSURE

Notebook Number: 16747-4 Test Site: Enfield, Ct.

Exposure Condition: OPT-90°C Size: 5 1/2" x 9" 2-cell

Construction: Glass(11861) / EVA 14747 /cells(11861) / Tedlar200BS30WH(68040)

Test	Exposure, Hours	1,000	2,000	3,000	4,000	5,000
	Test Date 11/2/83	12/14/84	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches	8.35	1.8	3.93	3.60	
Cells	Condition	1	1	1	1	
	Voltage, V_{oc}					
	Current, I_{sc}					
Metals	Cell Metalization	1	1	1	1	1
	Interconnects	2	2	2	2	2
	at edge:	1	1	C3	C3	C3
	internally:	C2	C2	C2	C2	C2
Encapsulation	Outer Cover	B	B		B	B
	Back Cover	1	1	1	1	1
	Sealant					
	Gasket					
	Pottant	1	1	1	1	A3
	Pottant + Copper	1	1	1	1	A2
	Pottant Delamination:	1	1	1	1	D2
	Cells + Metallization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
Notes		Glass fractured		Some small bubbles		

A = Discoloration
B = Broken, fractured
C = Corrosion
D = Delamination
E = Flow/melt

1 = No change
2 = Slight Change
3 = Noticeable
4 = Moderate
5 = Severe

MODULE EXPOSURE

Notebook Number: 16747-1 Test Site: Enfield, Ct.

Exposure Condition: OPT-105°C Size: 5 1/2" x 9" 2-cell

Construction: Glass (11861)/ EVA 9918 /Cells(11861) /EVA/Tedlar 200BS30WH - (68040)

Test	Exposure, Hours	1,000	2,000	3,000	4,000	5,000
	Test Date 11/2/83	12/14/84	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches	8.35	1.8	3.93	3.60	
Cells	Condition	1	1	2	4	
	Voltage, V_{oc}					
	Current, I_{sc}					
Metals	Cell Metalization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	at edge:	1	1	1	1	1
	internally:	1	1	1	1	1
Encapsulation	Outer Cover	1	1	1	B	B
	Back Cover	1	1	1	1	1
	Sealant					
	Gasket					
	Pottant	1	1	1	A2	A4
	Pottant + Copper	A3 E	A5 E4	A5 E5	A5 E5	A5 E5
	Pottant Delamination:	1	1	1	1	D3
	Cells + Metallization	1	1	1	1	A2
	Interconnects	1	1	1	1	A2
	Outer Cover	1		E4	E5	E5
	Back Cover	1	D4	D4	E5 D5	E5 D5
Notes				Strong color + bubbl around Copper mes Pottant delaminatin from glass-bubbles but no color.		

A = Discoloration
B = Broken/fractured
C = Corrosion
D = Delamination
E = Flow/melt

1 = No change
2 = Slight Change
3 = Noticable
4 = Moderate
5 = Severe

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MODULE EXPOSURE

Notebook Number: 1[illegible]47-2
Test Site: Enfield, Ct.
Exposure Condition: OPT-105° C
Size: 5 /2" x 9" 2-cell

Construction: Glass(11861)/EVA 16718A/cells(11861)/EVA/Tedlar 200BS30WH-(68040)

Test	Exposure, Hours	1,000	2,000	3,000	4,000	5,000
	Test Date 11/2/83	12/14/83	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches	8.35	1.8	3.93	3.6	
Cells	Condition	1	1	1	1	
	Voltage, V_{oc}					
	Current, I_{sc}					
Metals	Cell Metalization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	at edge:	1	1	1	1	1
	internally:	1	1	1	1	1
Encapsulation	Outer Cover	1	1	B	B	B
	Back Cover	1	1	1	1	1
	Sealant					
	Gasket					
	Pottant	1	1	1	1	A2
	Pottant + Copper	1	A2	A2	A2	A4
	Pottant Delamination:	1	1	1	1	1
	Cells + Metallization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
Notes			Glass fractured			

A = Discoloration
B = Broken/fractured
C = Corrosion
D = Delamination
E = Flow/melt

1 = No change
2 = Slight Change
3 = Noticeable
4 = Moderate
5 = Severe

MODULE EXPOSURE

Notebook Number: 16747-3 Test Site: Enfield, Ct.

Exposure Condition: OPT-105°C Size: 5 1/2" x 9" 2-cell

Construction: Glass(11861) /EMA 16717 /Cells(11861)/Tedlar200BS30WH(68040)

Test	Exposure, hours		1,000	2,000	3,000	4,000	5,000
	Test Date	11/2/83	12/14/83	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches		8.35	1.8	3.93	3.60	
Cells	Condition		1	1	1	1	1
	Voltage, V_{oc}						
	Current, I_{sc}						
Metals	Cell Metalization		1	1	1	1	1
	Interconnects		1	1	1	1	1
		at edge:	1	1	1	1	1
		internally:	1	1	1	1	1
Encapsulation	Outer Cover		1	1	1	1	B
	Back Cover		1	1	1	1	1
	Sealant						
	Gasket						
	Pottant		1	1	1	1	A2
	Pottant + Copper		1	A2	A2	A2	A4
	Pottant Delamination:		1	1	1	1	D3
		Cells + Metallization	1	1	1	1	1
		Interconnects	1	1	1	1	1
		Outer Cover	1	1	1	1	1
		Back Cover	1	1	1	1	1
Notes				Glass fractured			Signs of decolration now appearing.

A	= Discoloration	1	= No change
B	= Broken/fractured	2	= Slight Change
C	= Corrosion	3	= Noticable
D	= Delamination	4	= Moderate
E	= Flow/melt	5	= Severe

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MODULE EXPOSURE

Notebook Number: 16747-4 Test Site: Enfield, Ct.

Exposure Condition: OPT-105°C Size: 5 1/2" x 9" 2-cell .

Construction: Glass(11861) / EVA 14747 /cells(11861) / Tedlar200BS30WH(68040)

Test	Exposure, Hours	1,000	2,000	3,000	4,000	5,000
	Test Date 11/2/83	12/14/84	1/24/84	3/7/84	4/18/84	5/30/84
	Rainfall, Inches	8.35	1.8	3.92	3.60	
Cells	Condition	1	1	1	3	
	Voltage, V_{oc}					
	Current, I_{sc}					
Metals	Cell Metalization	1	1	1	1	1
	Interconnects	2	C2	C2	C3	C3
	at edge:	1	1	A3	A3	A3
	internally:	C2	C2	C2	C3	C3
Encapsulation	Outer Cover	1	1	B	B	B
	Back Cover	1	1	1	1	1
	Sealant					
	Gasket					
	Pottant	1	1	1	A3	A4
	Pottant + Copper	1	A2	A2	A2	A3
	Pottant Delamination:	1	1	1	1	1
	Cells + Metallization	1	1	1	1	1
	Interconnects	1	1	1	1	1
	Outer Cover	1	1	1	1	1
	Back Cover	1	1	1	1	1
Notes			Glass fractured			

A = Discoloration
B = Broken/fractured
C = Corrosion
D = Delamination
E = Flow/melt

1 = No change
2 = Slight Change
3 = Noticable
4 = Moderate
5 = Severe

1984

SOLAR CELL MODULE FABRICATION BY THE "SPLIT PROCESS

OPERATIONS

1. Receive release film in rolls 26 or 50" wide.
2. Receive substrate panels, 24" x 48", ribbed back, stacked on pallets.
3. Receive Craneglas 230 mat sheet in rolls, 24 or 48" wide.
4. Receive Epon 828 epoxy resin in tank truck.
5. Receive Versamid polyamide resin in tank truck.
6. Receive solar cell unbacked modules, 24"x 48", stacked on pallets.
7. Transfer Epon 828 to epoxy resin storage tank.
8. Transfer Versamid to polyamide resin storage tank.
9. Transfer release film rolls to stack station 2.
10. Transfer reusable spacer panel pallets to stack station 3.
11. Transfer substrate panel pallets to stack station 4.
12. Transfer Craneglas 230 rolls to stack station 5.
13. Automatically pump Epon 828 from storage tank to machine supply tank at stack station 6 as needed.
14. Automatically pump Versamid from storage tank to machine supply tank at stack station 6 as needed.
15. Transfer solar cell unbacked module pallets to stack station 7.
16. Load release film roll on unwind stand at stack station 2 after removing previous roll core.
17. Load pallet stack of reusable spacer panels on unload stand at stack station 3 after removing previous emptied pallet.
18. Load pallet stack of substrate panels on unload stand at stack station 4 after removing previous emptied pallet.
19. Load Craneglas 230 roll on unwind stand at stack station 5 after removing previous roll core.
20. Load pallet stack of solar cell unbacked modules on unload stand at stack station 7 after removing previous emptied pallet.
21. Load empty, clean wheeled stack rack on empty rack clamp at station 1 of circular 8 station stacking machine and lock rack to clamp.

22. Advance stack rack in rack clamp to station 2 and index.
23. At station 2, automatically cut a 26" x 50" sheet of release film and automatically index and place it on the stack rack.
24. Advance stack rack in rack clamp to station 3 and index.
25. At station 3, automatically take one reusable spacer panel from the panel stack and automatically index and place it on the stack rack on top of the release film, aligning one edge and one end with one edge and one end of the release film.
26. Advance stack rack in rack clamp to station 4 and index.
27. At station 4, automatically take one 24 " x 48" substrate panel, ribber side down, from the panel stack and automatically index and place it on the stack rack on top of the spacer panel, aligning one edge and one end with corresponding edges and end of other stack components.
28. Advance stack rack in rack clamp to station 5 and index.
29. At station 5, automatically cut a 24" x 48" sheet of Craneglas 230, and automatically index and place it on the stack rack on top of the substrate panel, aligning one edge and one end with corresponding edges and ends of other stack components.
30. Advance stack rack in rack clamp to station 6 and index.
31. At station 6, automatically measure, mix and dispense Epon 828/Versamid resin mixture onto the Craneglas 230 surface in a preprogramed pattern.
32. Advance stack rack in rack clamp to station 7 and index.
33. At station 7, automatically take one 24" x 48" solar cell unbacked module, cell side up, from the module stack and automatically index and place it on the stack rack on top of the resin-impregnated Craneglas, aligning one edge and one end with corresponding edges and ends of other stack components.
34. Advance stack rack in rack clamp to station 8 and index.
35. If stack rack contains fewer than 20 assemblies, advance stack rack in rack clamp to station 1 and repeat steps 22 through 34.
36. If stack rack co [illegible] assemblies, unlock fully loaded wheeled stack rack from clamp and [illegible] ing machine.

37. Place a few 24" x 48" x 20 lb fat sheet panels on top of the panel assemblies in the rack.

38. Roll the rack to a holding area and allow the panel assemblies to stand in the rack at room temperature for a minimum of four hours to allow the Epon 828/Versamid resin adhesive mixture to harden.

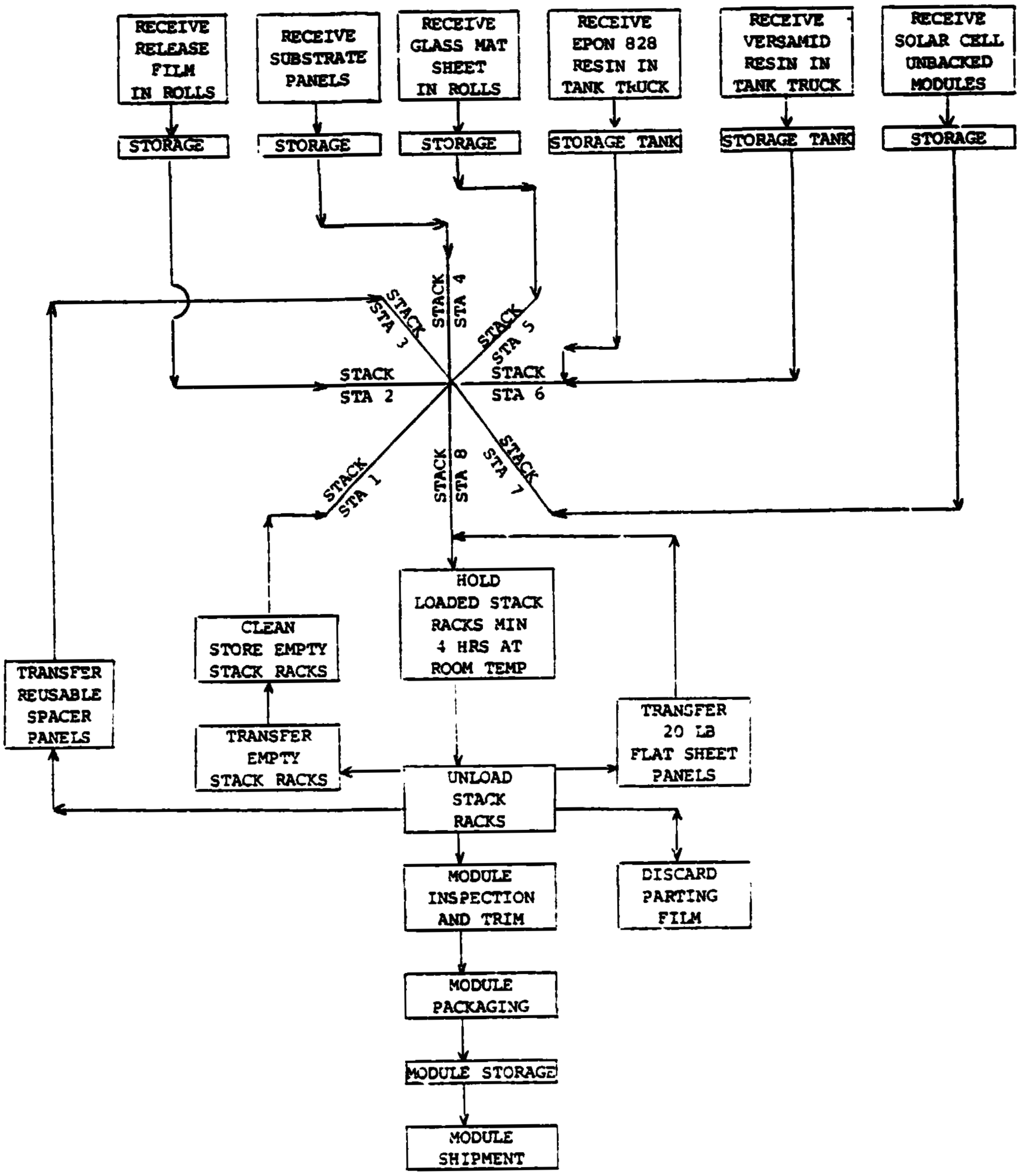
39. Remove the 24" x 48" x 20 lb flat sheet panels from the rack and return them to the vicinity of station 8 of the stacking machine.

40. Remove each solar cell assembly in turn from the rack.
41. Remove and discard the parting film.
42. Separate the reusable spacer panel and stack on a pallet for return to stack station 3.

43. Clean, trim, and inspect each solar cell assembly.
44. Pack each solar cell assembly in a corrugated shipping carton.
45. Convey the packaged solar cell assembly to a warehouse or shipping area.
46. Clean the stack rack and return it to station 1 of the stacking machine.

PRODUCTION FLOW CHART

SOLAR CELL MODULE FABRICATION BY THE "SPLIT" PROCESS



PROCESS COST ESTIMATE (1984 Estimated Costs)
SOLAR CELL MODULE FABRICATION BY THE "SPLIT" PROCESS
OUTPUT 50 MILLION SQ. FT./YR.

Operating Costs	Annual $	$ per Module	$ per Sq. Ft.	%
Variable				
Direct labor	2,583,000	0.4133	0.0517	23.10
Fringes on direct labor, 30%	774,900	0.1240	0.0155	6.93
Utilities	1,562,500	0.2500	0.0313	13.97
Freight in and out	375,000	0.0600	0.0075	3.35
Packaging	156,300	0.0250	0.0031	1.40
Maintenance supplies, 1% of 17,688,300	176,900	0.0283	0.0035	1.58
Maintenance labor, 1% of 17,688,300	176,900	0.0283	0.0035	1.58
Other supplies	312,500	0.0500	0.0063	2.79
By-products credits	---	---	---	---
	6,118,000	0.9789	0.1224	54.70
Fixed				
Indirect labor, 0.6 x direct labor	1,549,800	0.2480	0.0310	13.86
Fringes on indirect labor, 30%	464,900	0.0744	0.0093	4.16
Depreciation	2,166,700	0.3467	0.0433	19.37
Insurance and taxes, 3% of 17,688,300	530,600	0.0849	0.0106	4.74
Maintenance supplies, 1% of 17,688,300	176,900	0.0283	0.0035	1.58
Maintenance labor, 1% of 17,688,300	176,900	0.0283	0.0035	1.58
	5,065,800	0.8105	0.1013	45.30
Manufacturing cost*	11,183,800	1.7894	0.2237	100.00
Working capital* $411,900				
ROI before tax at 20% of 17,688,300 + 411,900	3,620,000	0.5792	0.0724	
Manufacturing cost + ROI*	14,803,800	2.3686	0.2961	

Capital Equipment and Buildings	Life	Annual Depreciation
$ 800,000	3 yrs	$ 266,700
11,368,300	7 yrs	1,624,000
5,520,000	20 yrs	276,000
$17,688,300		$2,166,700

*Based on listed manufacturing cost elements only. Does not include materials.

PROCESS COST ESTIMATE (1980 Estimated Costs)
SOLAR CELL MODULE FABRICATION BY THE "SPLIT" PROCESS
OUTPUT 50 MILLION SQ. FT./YR.

Operating Costs	Annual $	$ per Module	$ per Sq. Ft.	%
Variable				
Direct labor	2,097,900	0.3357	0.0420	23.90
Fringes on direct labor, 30%	629,400	0.1007	0.0126	7.17
Utilities	1,250,000	0.2000	0.0250	14.24
Freight in and out	312,500	0.0500	0.0063	3.56
Packaging	125,000	0.0200	0.0025	1.42
Maintenance supplies, 1% of 12,897,400	129,000	0.0206	0.0026	1.47
Maintenance labor, 1% of 12,897,400	129,000	0.0206	0.0026	1.47
Other supplies	250,000	0.0400	0.0050	2.85
By-products credits	---	---	---	---
	4,922,800	0.7876	0.0985	56.09
Fixed				
Indirect labor, 0.6 x direct labor	1,258,700	0.2014	0.0252	14.34
Fringes on indirect labor, 30%	377,600	0.0604	0.0076	4.30
Depreciation	1,572,300	0.2516	0.0314	17.92
Insurance and taxes, 3% of 12,897,400	386,900	0.0619	0.0077	4.41
Maintenance supplies, 1% of 12,897,400	129,000	0.0206	0.0026	1.47
Maintenance labor, 1% of 12,897,400	129,000	0.0206	0.0026	1.47
	3,853,500	0.6166	0.0771	43.9
Manufacturing cost*	8,776,300	1.4042	0.1755	100.00
Working capital* $323,200				
ROI before tax at 20% of 12,897,400 + 323,200	2,644,100	0.4231	0.0529	
Manufacturing cost + ROI*	11,420,400	1.8273	0.2284	

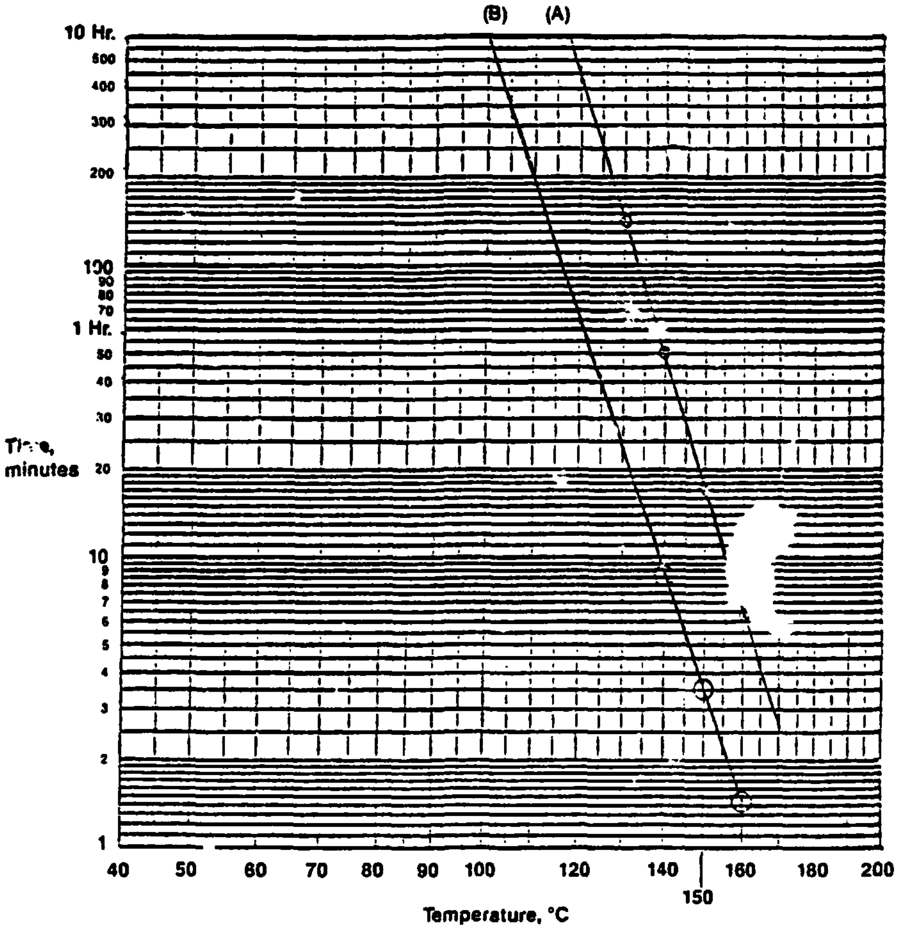
Capital Equipment and Buildings	Life	Annual Depreciation
$ 600,000	3 yrs	200,000
8,157,400	7 yrs	1,165,300
4,140,000	20 yrs	207,000
$12,897,400		$1,572,300

*Based on listed manufacturing cost elements only. Does not include materials.

Figure 1

V-4

Peroxide Half-Life Temperature Graph
(Time/Temperature for One Half-Life)



(A) "Lupersol" 101 peroxide; 5-Dimethyl-2,5-di(t-butyl peroxy) hexane

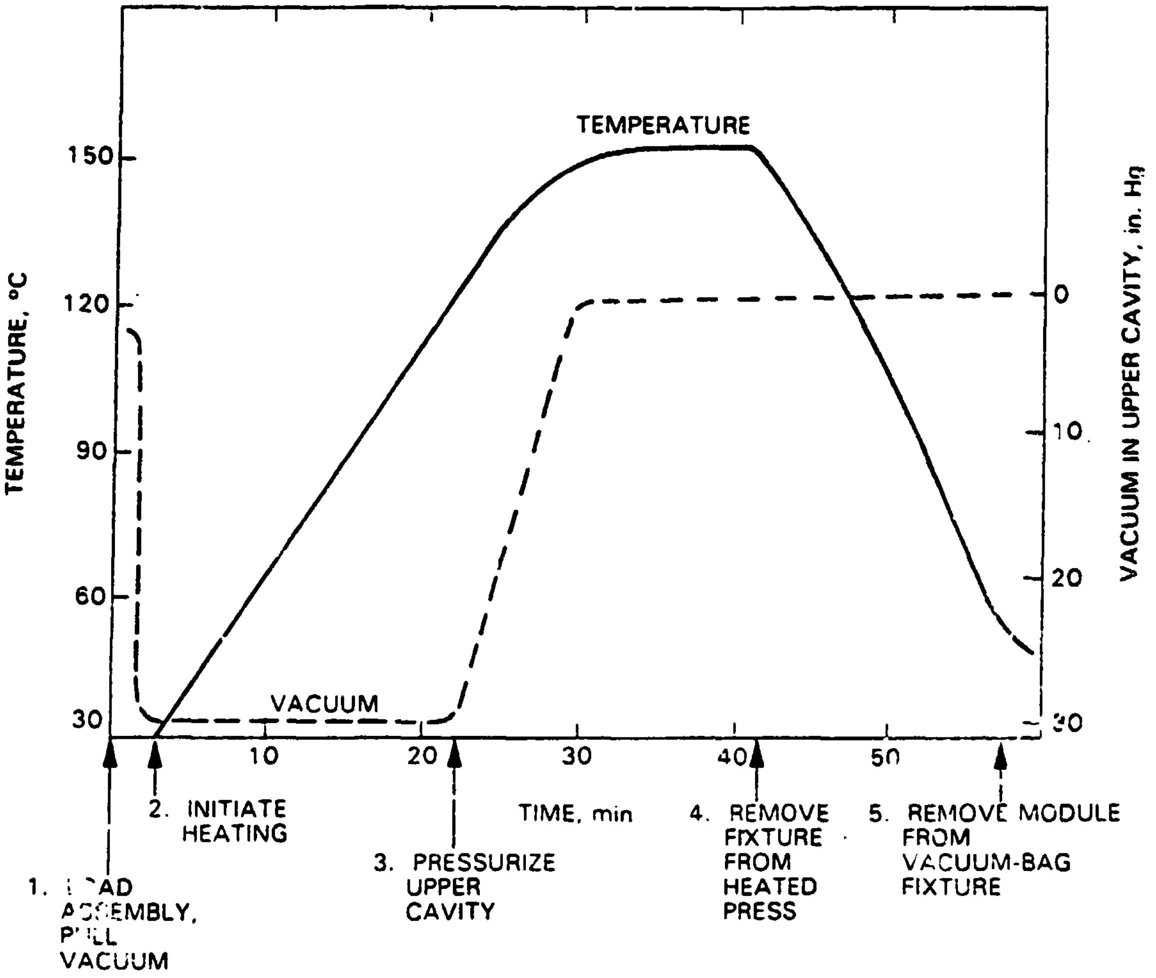
(B) "Lupersol" TBEC peroxide; OO-t-butyl O-(2-ethyl hexyl) monoperoxy carbonate

Source: Pennwalt Corporation, Lucidol Division, Buffalo, New York

Figure 2

Module Fabrication

Temperature-Pressure Schedule



STEPS

1. LOAD PREASSEMBLED MODULE INTO VACUUM-BAG FIXTURE AND PUMP BOTH CAVITIES DOWN TO 30 in. Hg FOR AT LEAST 5 min.
2. LOAD FIXTURE INTO PREHEATED PLATEN PRESS TO HEAT AT APPROXIMATE RATE OF 4°C/min BOTH CAVITIES ARE KEPT UNDER FULL VACUUM.
3. AT A TEMPERATURE OF 120°C, THE PRESSURE OF THE UPPER CAVITY IS GRADUALLY INCREASED TO ROOM PRESSURE OVER AN 8 TO 10-min PERIOD.
4. THE FIXTURE IS LEFT IN THE PRESS FOR 10 min AFTER REACHING A TEMPERATURE OF 150°C, THEN REMOVED WITH THE LOWER CAVITY STILL UNDER VACUUM.
5. THE MODULE CAN BE REMOVED FROM THE VACUUM-BAG FIXTURE AFTER COOLING FOR ABOUT 10 TO 15 min.

Figure 3

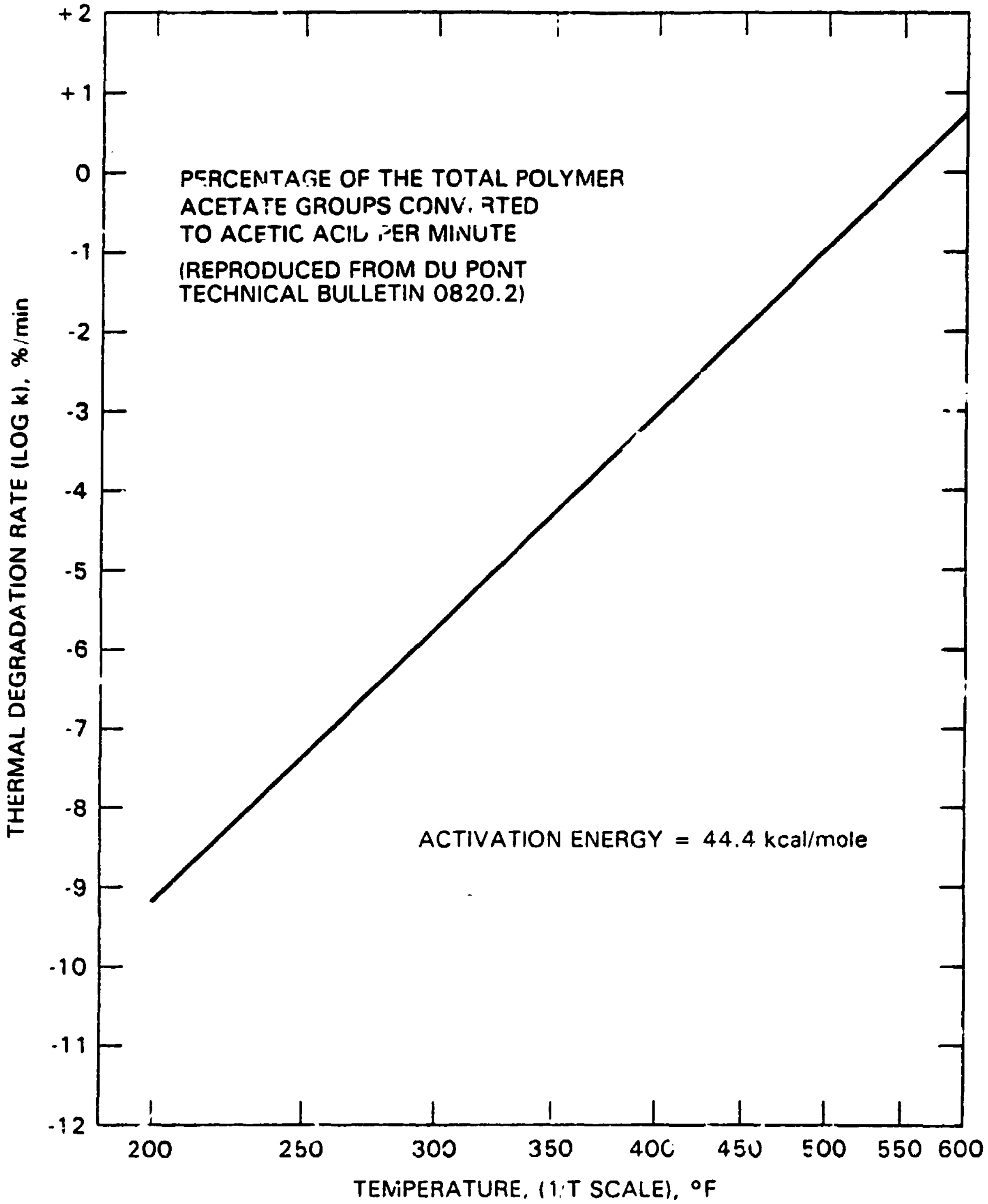

+2
+1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
THERMAL DEGRADATION RATE (LOG k), %/min
200
250
300
350
400
450
500
550
600
TEMPERATURE, (1/T SCALE), °F
PERCENTAGE OF THE TOTAL POLYMER ACETATE GROUPS CONVERTED TO ACETIC ACID PER MINUTE
(REPRODUCED FROM DU PONT TECHNICAL BULLETIN 0820.2)
ACTIVATION ENERGY = 44.4 kcal/mole

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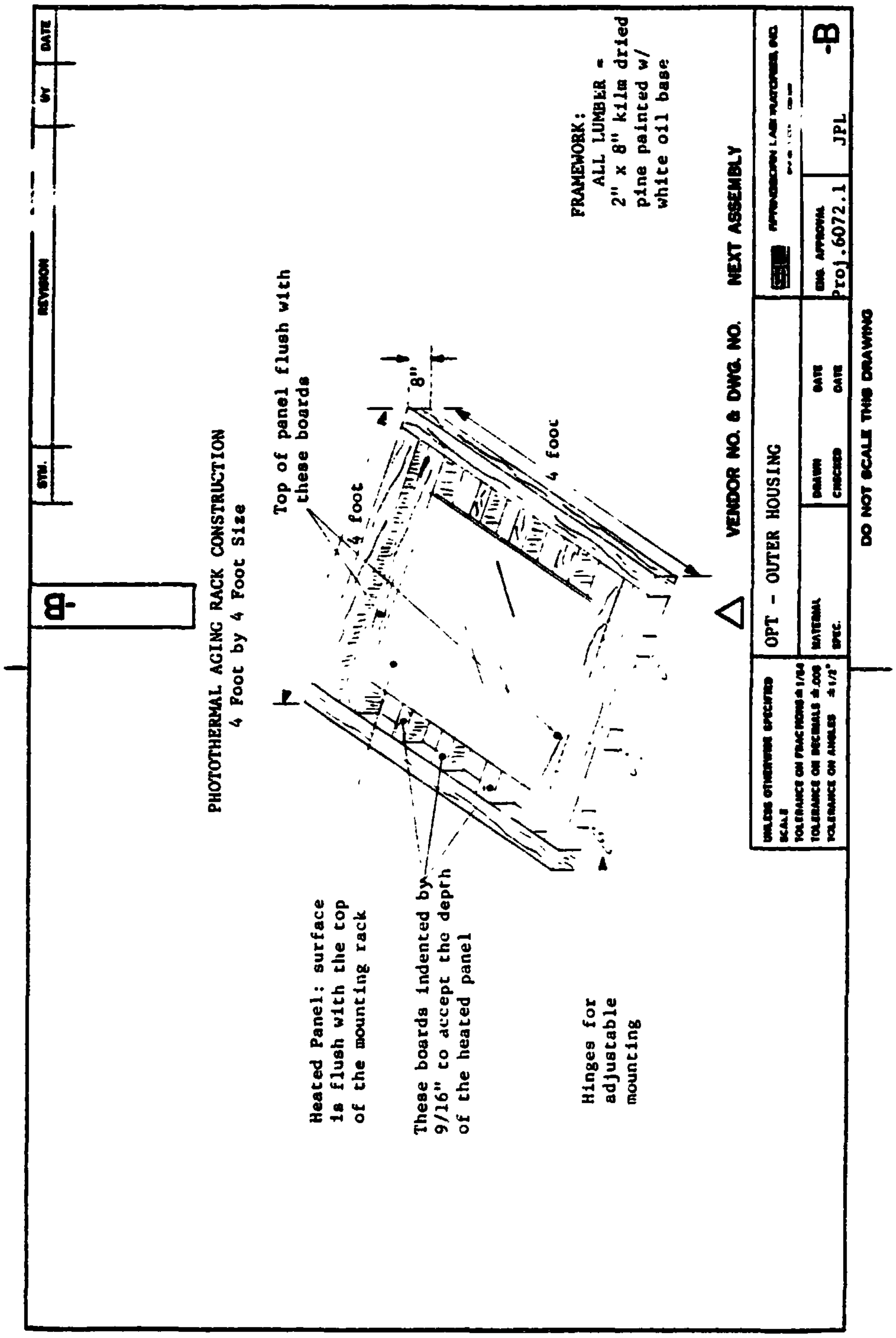
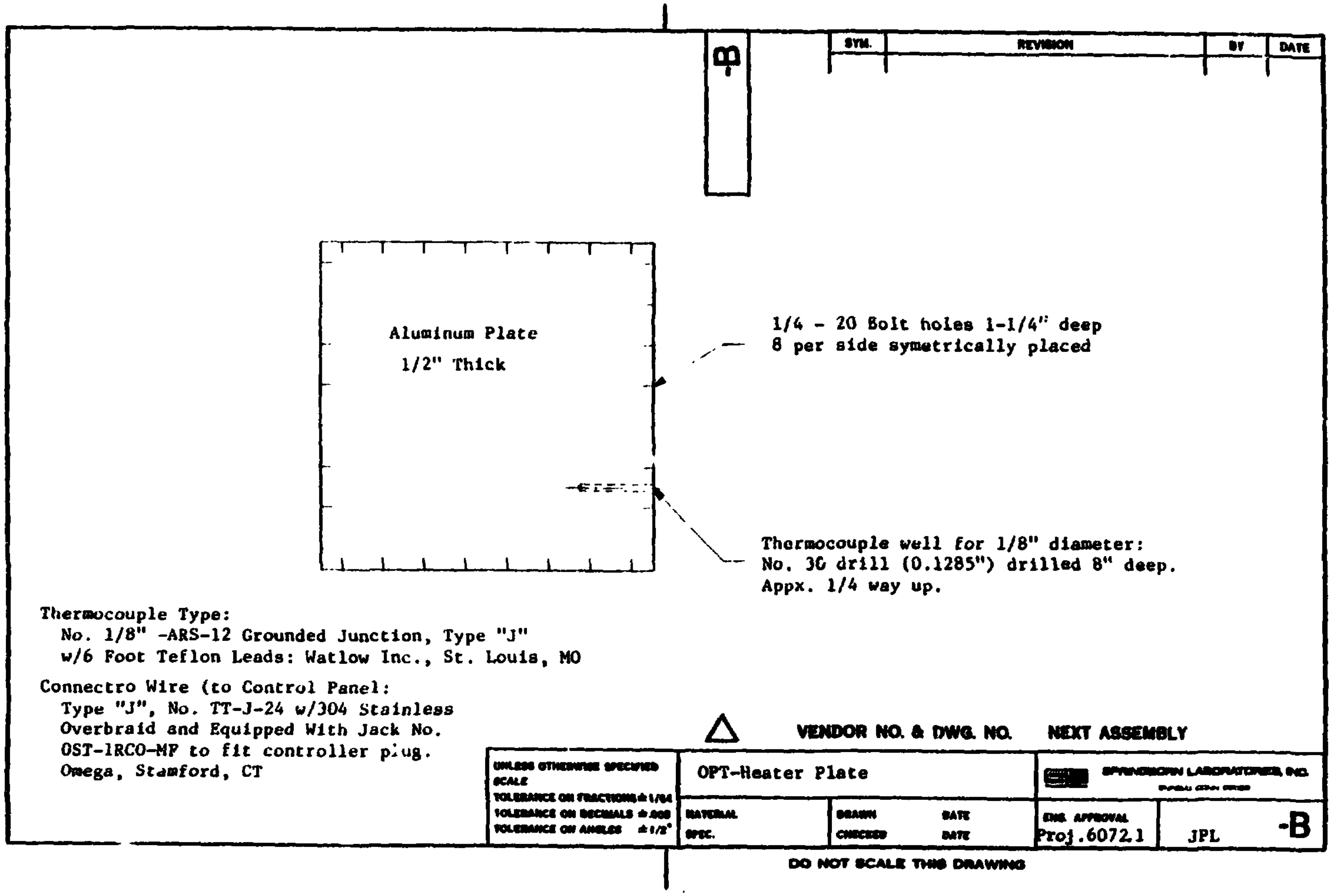
Figure 4



C-2

Figure 5



1/4 - 20 Bolt holes 1-1/4" deep
8 per side symetrically placed

Thermocouple well for 1/8" diameter:
No. 30 drill (0.1285") drilled 8" deep.
Appx. 1/4 way up.

Thermocouple Type:
No. 1/8" -ARS-12 Grounded Junction, Type "J"
w/6 Foot Teflon Leads: Watlow Inc., St. Louis, MO

Connectro Wire (to Control Panel:
Type "J", No. TT-J-24 w/304 Stainless
Overbraid and Equipped With Jack No.
OST-1RCO-MF to fit controller plug.
Omega, Stamford, CT

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Figure 6

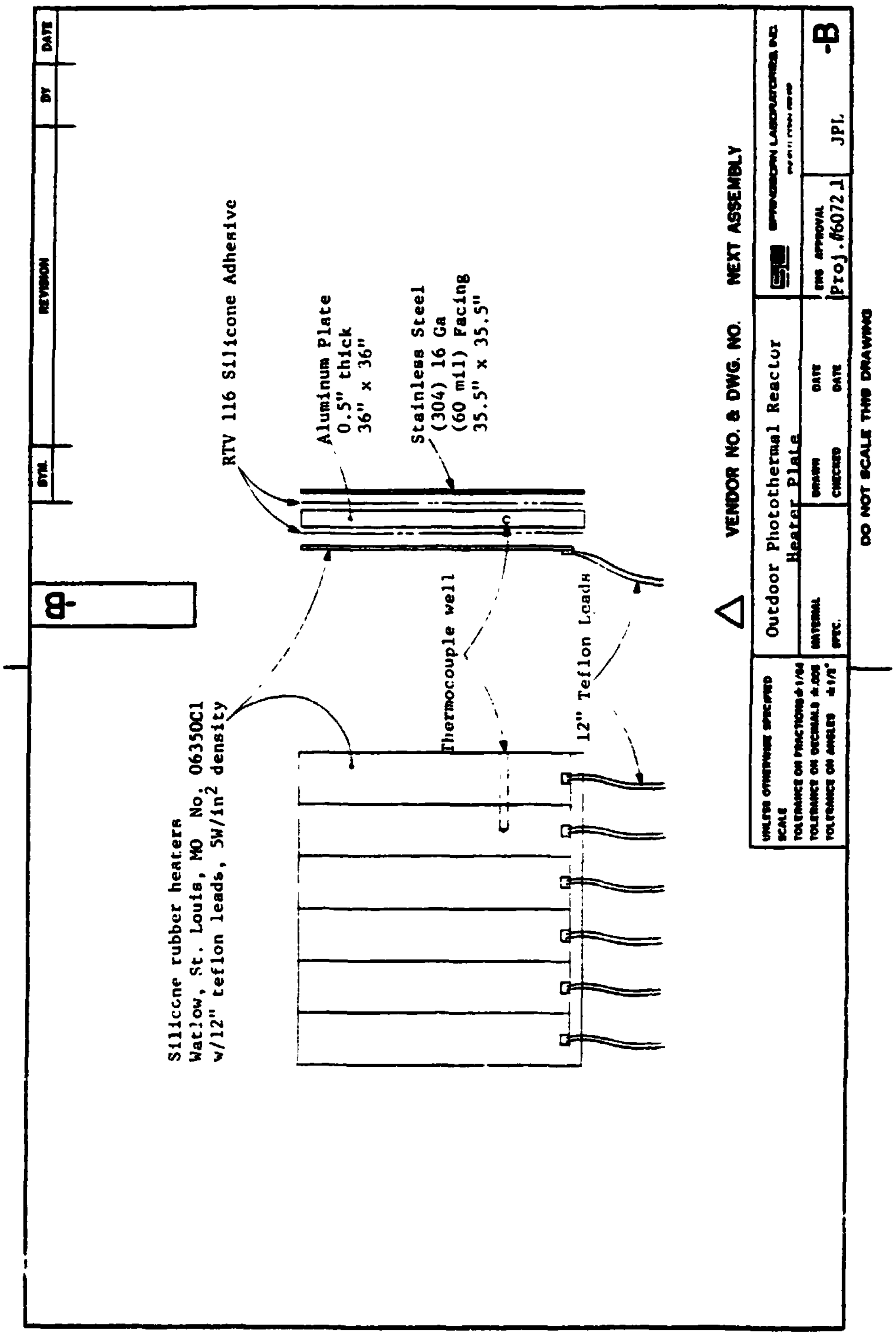
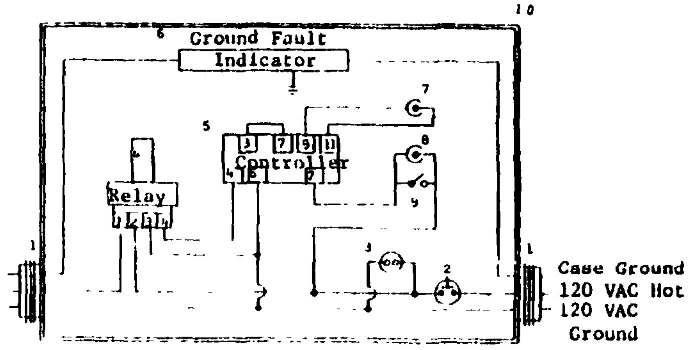


Figure 7

-B

SYM.	REVISION	BY	DATE

PHOTOTHERMAL AGING RACK CONTROLLER



1. Three prong connector for 60 amp. No. 6 wire cable.
2. Circuit breaker, 60 amp., 120 VAC
3. Neon indicator light, Allied Electronic, Hampden CT, 616-242X (housing) w/bulb NE-51H
4. Mercury relay, 75 amp switching, Watlow Electric St. Louis, Mo. No. H107-B00-A1, 120 V will switch 75 amps.
5. Controller 808 Watlow Electric, St. Louis, MO No. 8A15-71-C609 series. Takes "J" therrocouple.
6. Ground fault indicator circuit (optional)
7. Thermocouple connector, panel jack: JP-IRCO-F w/ RJACL adaptor plate. Omega Engineering, Stamford, CT
8. Photoswitch connector (Type BNC-Female) or (Timer Control)
9. Photoswitch bypass (SPST, 3A, 125 VAC)
10. Case, Allied Electronics, Hampden CT, No. 736-6700.

△ VENDOR NO. & DWG. NO. NEXT ASSEMBLY

UNLESS OTHERWISE SPECIFIED
SCALE
TOLERANCE ON FRACTIONS ± 1/64
TOLERANCE ON DECIMALS ± .005
TOLERANCE ON ANGLES ± 1/2°

OPT-CONTROLLER

MATERIAL
SPEC.

DRAWN DATE
CHECKED DATE

SPRINGBORN LABORATORIES, INC.

ENG. APPROVAL
Proj.6072.1

JPL

-B

DO NOT SCALE THIS DRAWING

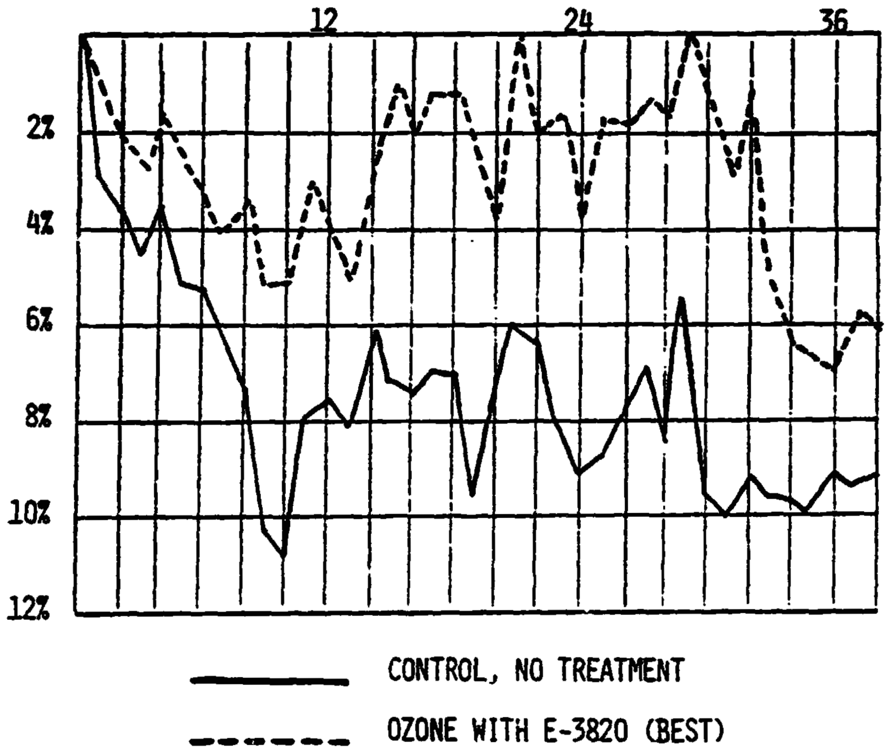
Figure 8

SOILING EXPERIMENTS

THIRTY-TWO MONTHS EXPOSURE
ENFIELD, CONNECTICUT

% LOSS IN I_{sc} WITH STANDARD CELL TREATED ACRYLAR
(SUPPORTED ON GLASS)

38 MONTHS EXPOSURE



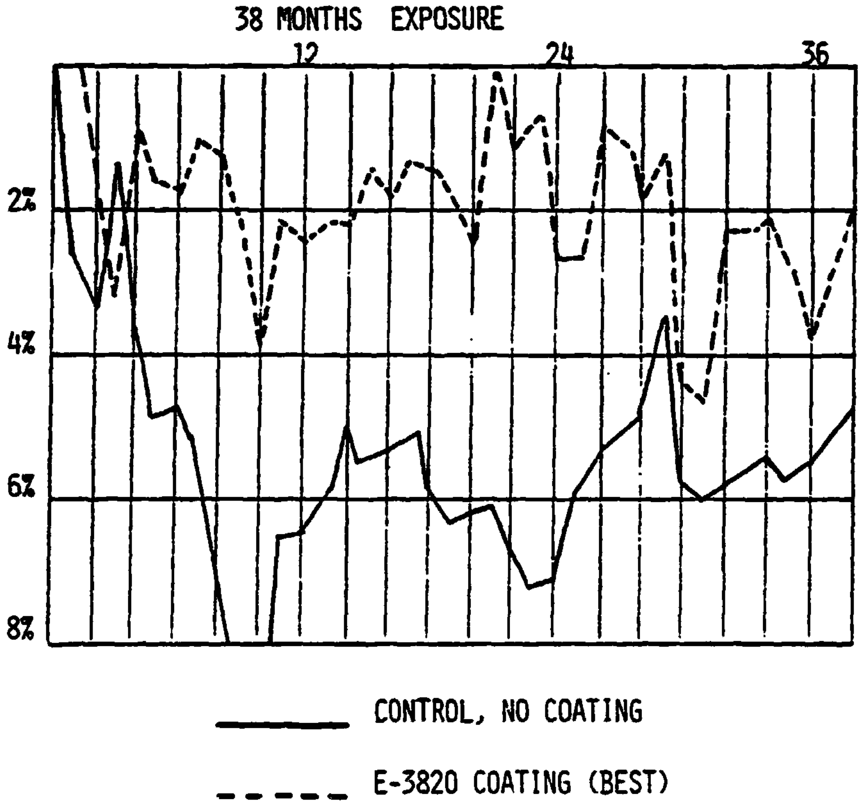
ESTIMATED AVERAGE POWER IMPROVEMENT, 3.9%

Figure 9

SOILING EXPERIMENTS

THIRTY-TWO MONTHS EXPOSURE
ENFIELD, CONNECTICUT

% LOSS IN I_{SC} WITH STANDARD CELL TREATED
TEDLAR 100BG30OUT
(SUPPORT ON GLASS)



ESTIMATED AVERAGE POWER IMPROVEMENT, 3.8%

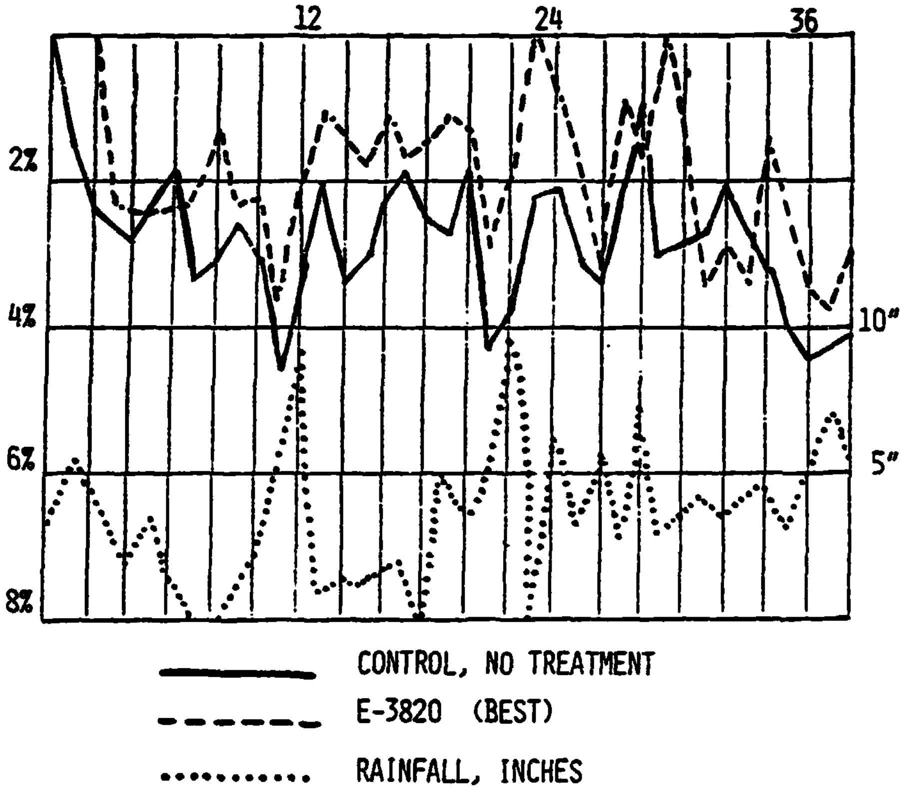
Figure 10

SOILING EXPERIMENTS

THIRTY-TWO MONTHS EXPOSURE
ENFIELD, CONNECTICUT

% LOSS IN I_{SC} WITH STANDARD CELL TREATED
SUNDEX GLASS

38 MONTHS EXPOSURE



ESTIMATED AVERAGE POWER IMPROVEMENT, 1%