September 1998 • NREL/SR-520-25296

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Final Report
January 1993—June 1997

W.W. Holley and S.C. Agro
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Enfield, Connecticut

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Prepared under Subcontract No. ZAG-3-11219-02

September 1998

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EXECUTIVE SUMMARY

Yellowing of EVA-based PV encapsulants in fielded modules has been observed and well documented over the past ten to fifteen years. The purpose of this three-phase PVMaT program was to further define the problem, research possible chemical mechanisms, and then combat the yellowing phenomenon by development of advanced PV encapsulants. Findings from each phase are highlighted below.

Phase I - Further Problem Definition: This phase comprised a literature search on EVA-based encapsulant browning, survey of and site visits to installations reporting discolored encapsulant in fielded modules, and analysis of browned EVA-based encapsulant. The purpose was to better understand the parameters influencing browning and the probable chemical mechanisms involved. Findings showed that the incidence of EVA-based encapsulant browning is not limited to the modules of any one manufacturer or the encapsulant sheet provided by any one supplier.

The incidence of EVA-based encapsulant browning appears to be primarily in the West and Southwest where there is comparatively high solar insolation and higher operating temperatures.

Also, EVA-based encapsulant browning appears to be more intense at test facilities that have a combination of high module operating temperature and high solar insolation.

Accelerated aging studies suggest that browning is not related to the EVA base resin. In particular, for one series of tests a "standard cure" A9918P encapsulant laminated between low iron glass showed significant yellowing after 17 weeks in a Xenon Arc Weather-O-Meter, while "neat" EVA resin, with no additives, showed little or no yellowing after the same exposure.

These studies also suggest that photochemistry of encapsulant browning is related to additives in the formulation, in particular Naugard P and an interaction between Lupersol 101 and Cyasorb UV-531 and not the EVA, unless the reaction products of Naugard P and Cyasorb UV-531 with Lupersol 101 are in turn involving the polymer in some way.

In a similar series of aging studies, when one additive at a time was systematically removed from A9918P, discoloration was greatly reduced. And when only one additive at a time was used in Elvax 3185, discoloration was greatly diminished or eliminated. Also, when "fast cure" 15295P was substituted for A9918P in some aging samples, the rate of yellowing was reduced by a factor of approximately 2.5 after 17 weeks in the Weather-O-Meter. The reduced yellowing appears to be a result of a different chemical composition for the peroxide in 15295P, Lupersol TBEC peroxide rather than Lupersol 101, the only difference between the two types of encapsulant.

Various analyses on browned and unaged EVA-based encapsulant corroborate the findings of the laboratory aging studies. Specifically, analytical investigations by IR and Raman spectroscopy, and indirectly by TGA and XPS, show no evidence of conjugated unsaturation in the EVA polymer, which tends to discount polyene chromophores as the mechanism for encapsulant browning. However, the analyses support an interaction of additives as a cause of browning.

Notably, residual unreacted Lupersol 101 peroxide remaining after curing of A9918P significantly reduces the concentrations of stabilizing additives based on GC/FID and GC/MS. Specifically Cyasorb UV 531 concentrations suffered little reduction in concentration when a glass/encapsulant/glass laminate of A9918P without Lupersol 101 was exposed in the Weather-O-Meter for ten weeks. But samples with the usual amount of Lupersol 101 peroxide exhibited a 40% drop in Cyasorb UV-531 concentration during 12 weeks Weather-O-Meter exposure. And consistent with aging studies, the latter showed significant yellowing while the former did not.

It is likely that transformation products of BHT (butylated hydroxytoluene, in the EVA resin from DuPont), Cyasorb UV 531, and nonyl phenol (from reactions of Naugard P), arising from reactions with alkoxy radicals from the photolysis of Lupersol 101 peroxide, play an important role in discoloration. As indicated before, Weather-O-Meter

aging studies showed a strong correlation between color development and additive/Lupersol 101 peroxide interactions.

Phase II - Development of Stabilization Strategies: Development work, including reformulation, has resulted in four experimental encapsulants with greatly reduced browning. After 40 weeks in the Weather-O-Meter, glass/glass laminates prepared with X9903P, X9923P, X9933P and 15303P showed no visible yellowing. Yellowness index was reduced by 10 to 20 versus A9918P. Control laminates with A9918P and 15295P were a dark brown. And after 40 weeks of accelerated outdoor EMMA exposure in Phoenix at a nominal 5 U.V. suns, glass/glass laminates prepared with X9903P show no measurable yellowing.

The use of cerium oxide-containing glass, Solarphire or Solite or Solatex II, greatly reduces the rate of discoloration of EVA-based A9918P and 15295P, presumably by filtering out much of the UV-B radiation (i.e., 280 to 340 nm). Thirty weeks exposure in the Weather-O-Meter of glass/15295P/glass samples with cerium-oxide containing glass produced a Yellowness Index of 5.2, undetectable by eye, and one year exposure gave a 13 Index. By contrast, after 30 weeks exposure a 15295P control prepared with Starphire low-iron glass had a Yellowness Index of 65 and a dark brown color.

After 18 months of accelerated outdoor EMMA exposure at a nominal 5 U.V. suns, 15295P laminates prepared with cerium-containing glass had no visible color while similar samples using A9918P had almost no visible color. Versus controls, Yellowness Index was reduced by a factor of approximately 15. When samples of A9918P were evaluated with Tefzel as the superstrate, there was no discoloration during long term accelerated aging by either Weather-O-Meter or by EMMA. Presumably sufficient oxygen gets through the Tefzel to photobleach any chromophores or perhaps to inhibit their formation.

However, there was one surprise. When the experimental encapsulants were evaluated in a mini-module format, there was browning of three of the encapsulants when used under Tefzel cover film. Since there is available oxygen in these systems, we suspect, for the following reasons, that a different mechanism may be taking place than under glass superstrates: 1) Browning occurred much more rapidly than with A9918P under glass, and 2) A9918P under Tefzel showed no browning after 26 weeks which is consistent with what we observed for Tefzel/glass laminates exposed to both Weather-O-Meter and EMMA.

In our proposal for this PVMaT program, we had suggested a "family of stabilization strategies" which would be adaptable to various module construction. While the experimental EVA-based encapsulants appear promising for modules with glass superstrates, in the case of Tefzel cover film the conventional A9918P or 15295P would be preferred.

Phase III - Full Scale Module Fabrication and Testing: The four experimental EVA-based encapsulants from Phase II were successfully prepared on a pilot scale using production equipment and the resulting sheet was used, without significant problems, by six different module producers to fabricate full-size modules. With only a couple of exceptions, curing of these modules was at a consistently high level, with average gel content greater than 83% versus a typical 80% for current EVA-based materials.

A total of 102 modules prepared with the four experimental encapsulants were subjected to IEEE 1262 qualification testing. Except for yellowing of one experimental formulation, X9933P, there was not a single failure related to the encapsulant material.

The yellowing of X9933P occurred in the modules of several manufacturers, so it was not an anomaly. However, the quality of the yellow, a bright canary yellow, was quite different than the yellowing seen in X9918P during early stages of discoloration. We suspect a different mechanism. This formulation has been dropped from serious consideration, but has been included in the modules on the two-axis tracker.

During IEEE 1262, modules were subjected to damp heat (85°C/85% R.H.), thermal cycling, U.V., etc. Despite these exposures there appeared to be little or no loss of adhesion to cells, interconnects or glass. However, on a

qualitative basis, some backing film laminates showed a loss of adhesion to the encapsulant as a result of damp heat. These backings also developed a brown discoloration which was traced to the adhesive/tie layer.

Finally, a total of 36 modules, representing four different experimental encapsulants and six separate manufacturers were deployed on a two-axis tracker at the STAR facility of Arizona Public Service in Tempe. Another 12 controls modules, prepared with A9918P, were installed several months later.

These modules are being monitored and tested by personnel from the Photovoltaic Testing Laboratory of Arizona State University. After 18 months on the tracker none of the modules have shown any discoloration or loss of power.

An expanded family of encapsulants is now commercially available in sheet form from STR for use by module manufacturers for a variety of constructions and applications. However, it is essential that module makers perform their own evaluation of these encapsulants in their module design(s) of interest.

INTRODUCTION

The goals of the NREL PVMaT program are, among others, to reduce module manufacturing costs and improve the quality, and we might add here the reliability, of manufactured PV products. But lower production costs will require economies of scale, and this means that the large potential market of central power generating stations needs to be opened up. In a 1989 report, DOE concluded, "...that utilities are 'a key factor in achieving large-scale markets' that would drive down costs." [1]

The report goes on to say, "However, in general, utility companies are not ready to embrace the PV technology on a large scale, in spite of several potential advantages of PV as a large-scale power-generating source." [1] Electric utilities seem to be in a "wait-and-see" mode, and show no interest at the present time in making investments of the magnitude that would make PV more competitive with other power sources.[1]

One component critical to the service life of PV modules is the useful life of the EVA-based encapsulant which is employed extensively by module manufacturers on a worldwide basis. This pottant has been in commercial use since 1982[2], and over that time has proven to be a dependable material from the standpoint of production, module fabrication, and end-use. But despite the widespread acceptance of EVA-based encapsulants for PV, some module producers, end-users, and investigators have reported a yellowing or browning phenomenon with EVA-based formulations in the field. While the incidence of this discoloration/degradation appeared at comparatively few sites at the time that this present program was conceived, it raised serious concern as to the long term reliability of EVA-based encapsulation systems.

Most notable was the browning degradation of the EVA-based encapsulant at Carrizo Solar Corporation's Carrizo Plains Photovoltaic Power Plant in California, which had a profound effect on the PV industry with respect to consumer confidence and reliability standards. The news of the browning and ultimate demise of this plant quickly transcended boundaries of small circulation PV industry newsletters, making headlines in national publications such as Barron's.

Surprisingly, while there had been considerable discussion of the discoloration/degradation of EVA-based encapsulant in the industry at the time this study was proposed to NREL, there was insufficient published information from which to draw firm conclusions regarding its cause(s).

Consequently, under the NREL PVMaT program, STR (formerly Springborn Laboratories) proposed to conduct a thorough review of published information and internal reports and documentation, where available, from proposed PVMaT team members and other sources. More importantly, STR proposed to conduct a detailed survey of module manufacturers, primarily proposed team members *(see Appendix A - Team Member List)* - both those who had experienced encapsulant discoloration and those who had not, with an emphasis on well documented case histories.

Prior to December 1992, the discoloration of EVA-based encapsulant, reported at the Carrizo Plains facility had been attributed to high operating temperatures, approximately 90° C, and increased light intensity resulting from mirror-enhanced light exposure (3,4,5). It is interesting that field survey findings on modules operated at normal conditions of temperature and light intensity were consistent with this speculation - that is, the discoloration was not nearly as severe with these other modules as that experienced at Carrizo Plains.

The Phase I survey of case histories of EVA-based encapsulant discoloration in fielded modules in the U.S., conducted during the first year of this program, revealed that the problem is limited to areas of the West and Southwest that have comparatively high solar insolation and ambient temperature. There has been only one confirmed case of discolored EVA-based encapsulant from modules fielded in the Northeast, and that occurred after 12 years in Maryland.

The absence of hard data regarding module operating temperatures, solar insolation, onset of discoloration, and quantitative evaluation has made correlations difficult, if not impossible. However, the degree of discoloration

does appear to correlate with increasing average daily direct normal solar radiation and approximate maximum module operating temperature, as estimated from maximum ambient temperatures.

From this survey, it is clear that the discoloration problem is not limited to modules of any one manufacturer, however, the rate and degree of discoloration do appear to vary from company to company. Also, discoloration is not limited to EVA-based encapsulant sheet from any one supplier.

Over the course of the first year of this program, an accelerated U.V. aging method was selected. On careful review of the various types of accelerated U.V. aging equipment available, an Atlas Ci35A Weather-O-Meter Xenon Exposure System was selected as appropriate equipment for this work. (Note: Ci-65 would have been preferred) To summarize, some of the more significant advantages of the Ci35A include:

1. The spectral irradiance of filtered Xenon light in the UV and visible range of the spectrum closely resembles that of natural sunlight, with no large spikes as are often found with mercury lamps or carbon arc sources.

2. The xenon-arc source is widely accepted by industry (e.g. textile, automotive, plastic) and Government for accelerated weathering.

3. The Ci35A is flexible in that the operator is able to set, monitor, and control the irradiance, temperature, humidity, and water spray.

4. The Ci35A has capacity for many more samples than table top models - more than sixty 2.6 x 5.0 inch samples, and twice that number if 2.6 x 2.5 inch samples are used. This is particularly important considering the scope, not only of the Task 2 problem definition studies, but also Task 5 evaluation of improved encapsulant formulations.

Disadvantages of xenon-arc include degradation of filters and air-cooled lamp, requiring periodic replacement of both, and comparatively high cost of the equipment and replacement parts.

On balance, however, this device was superior to any others. Consequently, a Ci35A device was purchased for utilization on the program, and was calibrated for black panel temperature and irradiance.

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5) J. Schaefer, L. Schlueter, A. Rosenthal, H. Wenger and A.E. Luque, Electrical Degradation of the Carrizo Plains Power Plant, E.C. Photovoltaic Solar Energy Conf., Proceeding Int. Conf., 10th, pp. 1248-1253, (1991).

1.0 LITERATURE SEARCH AND SURVEY ON EVA DISCOLORATION

The following twenty pages details the results of the Phase I information search and survey. This study was undertaken to gain additional insights on the discoloration problem to help guide subsequent laboratory problem definition and development work.

Section 1.1 and 1.2 cover the literature search on encapsulant browning, detailing field aging observations and laboratory investigations, respectively. Under each subsection we have, where possible, summarized reported results and then followed this with detailed findings by the various investigators.

Section 1.3 reports on a survey of alternative polyolefin base resins to the Elvax 3185 EVA currently being used in 15295P and A9918P encapsulant. Section 1.4 covers survey, assessment and selection of accelerated U.V. aging methods.

Finally, section 1.5 details the results of the field survey. This study covers those installations where browning had been reported and in some cases involved trips to those sites by STR staff to view the phenomenon first hand.

1.1 Studies of EVA-Based Encapsulant Discoloration/Degradation in Fielded Modules

Overview: Published reports on browning of EVA-based encapsulants in fielded modules were mostly qualitative and incomplete. Since it was a new phenomenon, it generally went unnoticed until the discoloration was fairly advanced. Consequently, estimates of the elapsed time for browning to first occur varied considerably with investigators and locations.

While browning was more prevalent in mirror enhanced arrays, non-mirror enhanced modules also experienced discoloration. There were varying opinions as to the amount of power loss with browning, but it was generally agreed that there was at least some measurable loss.

It was also clear that a field survey was needed as part of this PVMaT project in order to confirm some of the reported information.

Detailed findings: Comparatively little technical information has been published on the experience of EVA-based encapsulant discoloration/degradation in fielded modules, and most which has appeared has only been released since late in 1990. EVA-based encapsulant discoloration was discussed in detail at a meeting held at SERI in February 1990 between selected module manufacturers, SERI staff, and representatives from Springborn Laboratories, Inc. In October of that year, A. Rosenthal and C. Lane of Southwest Technology Development Institute prepared a paper reporting on "EVA degradation" at the now notorious Carrizo Solar Photovoltaic Power Plant, Carrizo Plains, CA.[1,2]

The Carrizo plant was constructed by ARCO Solar (now Siemens) between 1983 and 1985, and was intended as a "demonstration of photovoltaics' potential for commercial power production."[3] The facility comprised ten segments, each with its own PCU (power conditioning unit). Each of the first 9 segments employed 84 mirror-enhanced, 2-axis trackers (Carrizo 1A), while segment 10 (Carrizo 1B) used 43 larger trackers, but without mirror enhancement. Concentrated solar radiation from the mirrors was reported to be equivalent to a nominal 2 suns.

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1 J. Galica, Internal Memorandum, Springborn Laboratories, Covering Meeting at SERI, Feb. 22, 1990, (Feb. 26, 1990).

2 A. L. Rosenthal and C. G. Lane, Solar Cells Their Science, Technology, Applications and Economics, Field Test Results for the 6 MW Carrizo Solar Photovoltaic Power Plant, (Elsevier Sequioa, 1991).pp. 563-571.

3 J. Schaefer, L. Schlueter, A. Rosenthal, H. Wenger and A. E. Luque, Electrical degradation of the Carrizo Plains power plant, E. C. Photovoltaic Sol. Energy Conf., Proc. Int. Conf., 10th, P1248-53, (1991).

ARCO indicated that discoloration of EVA-based encapsulant was first noted in Carrizo 1A modules after approximately 2.5 years of field exposure, and J. Schaefer of EPRI et. al., reports that the facility experienced "steady degradation in electrical performance since 1986." As of February 1990, discoloration of modules in the mirror-less Carrizo 1B had just started to occur, and J. Schaefer reported "less, but increasing, browning as of 1991."

It might be noted that this site was visited by STR program team members in late March 1992. They reported that segment 10 continued to brown (darken) and was at that time perhaps half as brown as the mirror enhanced segments.

Since this discoloration phenomenon was unexpected, two complications arose, not only for this site but also for other locations where encapsulant discoloration has been observed. Because discoloration occurred only over the dark blue-grey silicon cells, it is not clear exactly when the change began; it may have gone unnoticed for some time.

Secondly, because the focus of evaluations was on module performance, discoloration was only considered a side issue, and consequently was never quantified. So various terms have been used to describe the discoloration, such as yellowing, browning, brown cell, amber, and degradation, but all of them only qualitatively at best.

Early in 1990 a major module manufacturer claimed to have seen evidence of browning in modules produced by four different manufacturers, but would not at that time disclose the names of those producers.[4] This same manufacturer reported that discoloration had been noted in its own modules both at Southwest Regional Experimental Station (Southwest RES), Las Cruces, NM, and at Southeast Regional Experimental Station (Southeast RES), Cape Canaveral, FL.

Since that time, J. Schaefer et. al. have reported evidence of "brown cells" in modules of manufacturers, other than ARCO (Siemens), at Las Cruces, NM, and San Ramon, CA.[5] Also, F.J. Pern and A. Czanderna claim reports of "yellowing of EVA" in non-mirror-enhanced arrays at Phoenix, AZ; Las Cruces, NM (Southwest RES); Albuquerque, NM (likely the Solarex array at Sandia as noted below); Cape Canaveral, FL (likely Southeast RES); as well as in Morocco, Australia, Saudi Arabia, and Nambia, South Africa.[6]

Regarding discoloration and power loss, Pern and Czanderna state, "Wide variations in the performance of PV modules have been reported ranging from essentially no loss in 10 years with discernible yellowing to over 40% loss in 5 years and forming a dark brown color." And they have indicated exposure times for the onset of discoloration ranging from 3 to 12 years.[7]

In September 1992, at the PV Performance and Reliability Workshop, C. Whitaker of ENDECON reported on module reliability at Pacific Gas & Electric's PV Test Facility (PTF) in San Ramon, CA, near Oakland. This site contains roughly 75 modules from 27 module manufacturers worldwide, and represents a variety of module types, constructions, and placements, both fixed and tracked. Roughly a dozen modules use a "concentrator" of some type.[8]

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4 J. Galica, Internal Memorandum, Springborn Laboratories, Covering Meeting at SERI, Feb. 22, 1990, (Feb. 26, 1990).

5 J. Schaefer, L. Schlueter, A. Rosenthal, H. Wenger and A. E. Luque, Electrical degradation of the Carrizo Plains power plant, E. C. Photovoltaic Sol. Energy Conf., Proc. Int. Conf., 10th, P1248-5, (1991).

6 F. J. Pern and A. W. Czanderna, AIP Conference Proceedings 268 Photovoltaic Advanced Research and Development Project, Rommel Noufi, (American Institute of Physics, New York, 1992), p. 445-451.

7 F. J. Pern and A. W. Czanderna, Solar Energy Materials and Solar Cells, Characterization of Ethylene Vinyl Acetate (EVA) encapsulant: Effects of Thermal Processing and Weathering Degradation on its Discoloration, (Elsevier Science Publishers, 1992).pp. 3-23.

8 C. Whitaker, Pacific Gas and Electric Company's Perspective on Module Reliability, Photovoltaic Performance and Reliability Workshop, (1992), p. 279-289.

According to Whitaker, "approximately 9 PTF modules show various degrees of browning." Again, little detail was provided, and it is not clear if the affected modules were all supplied by one manufacturer or whether they used a concentrator.

Module producer Solarex has reported two instances of EVA-based encapsulant discoloration, both in non-mirror-enhanced arrays. After 8 years of exposure in Albuquerque, the "Sandia Array" showed some encapsulant darkening in the center 7 cm x 7 cm area over 9.5 cm x 9.5 cm cells.[9] But Solarex reported no measurable power loss from the array as of September 1992, and no measurable power loss from modules returned to the Solarex plant for "flash tests."

In addition, Solarex reported visible browning of modules after 9 years exposure at Southwest RES in Las Cruces, NM, but again claimed no power loss and also indicated that browning disappeared "when textured glass is covered with alcohol."

At best, information on discoloration of EVA-based encapsulants in fielded modules was vague and incomplete. This fact prompted a more detailed survey of case histories of discoloration in the field as discussed in section 3.0 of this report.

1.2 Laboratory Studies of EVA-based Encapsulant Discoloration/Degradation

In laboratory studies of fielded, glass-superstrate PV modules, which had been in service for more than five years and in which the EVA-based encapsulant was discolored/degraded, Pern and Czanderna found a gradient to the yellowing or browning. Cross-sections of encapsulant were discolored on the glass side, but were clear in the remainder, down to the cell.[10] Other investigators have made similar observations.[11] In addition, "EVA in direct contact with the Silicon solar cell top surface displays a yellow-brown image pattern identical to that of the metallization grid lines and buslines underneath."

As experienced in the field, Pern and Czanderna found in the lab that there was reduction in cell efficiency for EVA-encapsulated test cells exposed to accelerated aging, that ranged from 0.5 to 3.1% for those with light-yellow EVA to 10.1 to 19.3% for test cells containing brown encapsulant.[12]

What appears to be causing this phenomenon?

The following sections will attempt to examine in a systematic way those factors, as reported in the literature, that appear to be contributing to EVA-based encapsulant discoloration/degradation and associated loss in module efficiency. These parameters include elevated temperature, U.V. light, the combination of high temperature and U.V., and effects of module construction, as well as catalytic effects of acetic acid and metal and metal oxide interfaces. Also reviewed are reported findings of "photo-bleaching" of discolored encapsulant, effects of aging on EVA structure, and the impact on additive levels.

1.2.1 Effects of Temperature:

Overview: At the moderate temperatures to which fielded modules are subjected (e.g. 60 to 85° C), both mirror-enhanced and not, temperature alone does not appear to be causing the discoloration phenomenon. That

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9 J. H. Wohlgemuth and R. C. Petersen, Photovoltaic Performance and Reliability Workshop, September 16-18, 1992, Golden, CO, Laxmi Mrig, (1992), p. 313-326.

10 F. J. Pern and A. W. Czanderna, Solar Energy Materials and Solar Cells, Characterization of Ethylene Vinyl Acetate (EVA) encapsulant: Effects of Thermal Processing and Weathering Degradation on its Discoloration, (Elsevier Science Publishers, 1992).pp. 3-23.

11 J. Galica, Internal Memorandum, Springborn Laboratories, Covering Meeting at SERI, Feb. 22, 1990, (Feb. 26, 1990).

12 F. J. Pern, Photovoltaic Performance and Reliability Workshop, September 16-18, 1992, Golden, CO, Laxmi Mrig, (1992), p. 327-344.

yellowing of EVA encapsulant in fielded modules is not uniform through the cross section, but proceeds from the glass superstrate inward, leads us to conclude that U.V. radiation, in addition to temperature, is required for yellowing/browning at these comparatively low temperatures.

Detailed findings: Thermolysis of EVA by deacetylation at elevated temperatures is well known, leading to acetic acid as the main decomposition product and unsaturated groups in the backbone of the polymer.[13] Where vinyl acetate homopolymer blocks occur, especially in high vinyl acetate content grades of EVA such as the Elvax 150 used for PV encapsulation, thermolysis was thought to result in formation of polyenes or conjugated unsaturated sequences that could cause yellow color development.

This degradation occurs in the absence of U.V. radiation at 150° C, and possibly lower temperatures, and the rate is reported to increase with increasing vinyl acetate content in the EVA copolymer.[14]

While 150° C exposure of modules in end-use is not expected, deacetylation at this temperature remains significant to PV applications. Liang et. al. state, "it was observed that during outdoor deployment, hot spots (up to 150° C) are developed in the PV modules. These hot spots can cause accelerated degradation leading to premature failure of the encapsulant."[15]

But what about the effect on EVA-based encapsulants of more moderate temperature exposure?

Wohlgemuth and Petersen reported that when EVA-encapsulated minimodules were given a high temperature soak at 130° C for 7,200 hours, there was "major mechanical and optical degradation," thermolysis of the EVA, and evolution of acetic acid.[16] But these same investigators indicated that when EVA-encapsulated minimodules with glass substrate and superstrate were heated for 5,303 hours at 125° C, there was no odor of acetic acid and yellowing only approximately 3.5 cm in from the cell edges.[17] Module operating current was reduced by 1.5 to 2%, but there was no change in fill factor or voltage.

Wohlgemuth and Petersen concluded that within expected limits of operation of PV modules, yellowing or browning is not caused by temperature alone.[18]

In 1983, Liang reported that when EVA-based (A9918) films were heated at 105° C for 800 hours in the absence of U.V. light, there was a gradual increase in absorption at wavelengths longer than 400 nm, which coincided with the appearance of yellowing of the EVA.[19] More recently, Pern and Czanderna reported that, "Heating EVA in capped vials in an oven (no light available) from 85-130° C for 120 h to 240 h results in increased yellowing."[20]

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13 B. A. Sultan and E. Sörvik, Thermal degradation of EVA (ethylene-vinyl acetate copolymer) and EBA (ethylene-butyl acrylate copolymer) - a comparison. I. Volatile decomposition products, J. Appl. Polym. Sci, 43, 1737-45 (1991).

14 B. A. Sultan and E. Sörvik, Thermal degradation of EVA (ethylene-vinyl acetate copolymer) and EBA (ethylene-butyl acrylate copolymer) - a comparison. II. Changes in Unsaturation and Side Group Structure., J. Appl. Polym. Sci, 43, 1748-59 (1991).

15 R. H. Liang, S. Chung, A. Clayton, S. Di Stefano, K. Oda and S. D. Hong et al., Photothermal degradation of ethylene/vinyl acetate copolymer, Polym. Sci. Technol, 20, 267-78 (1983).

16 J. H. Wohlgemuth and R. C. Petersen, Photovoltaic Performance and Reliability Workshop, October 25-26, 1990, Lakewood, CO, Laxmi Mrig, (1990), p. 247-258.

17 J. H. Wohlgemuth and R. C. Petersen, Photovoltaic Performance and Reliability Workshop, September 16-18, 1992, Golden, CO, Laxmi Mrig, (1992), p. 313-326.

18 J. H. Wohlgemuth and R. C. Petersen, Photovoltaic Performance and Reliability Workshop, September 16-18, 1992, Golden, CO, Laxmi Mrig, (1992), p. 313-326.

19 R. H. Liang, S. Chung, A. Clayton, S. Di Stefano, K. Oda and S. D. Hong et al., Photothermal degradation of ethylene/vinyl acetate copolymer, Polym. Sci. Technol, 20, 267-78 (1983).

20 F. J. Pern and A. W. Czanderna, AIP Conference Proceedings 268 Photovoltaic Advanced Research and Development Project, Rommel Noufi, (American Institute of Physics, New York, 1992), p. 445-451.

But Wohlgemuth and Petersen reported that when minimodules were subjected to a 90° C temperature soak for 7,200 hours, there was "no change." [21]

One factor that needs to be taken into account regarding heat induced yellowing of EVA-based encapsulant is the presence or absence of oxygen. In 1983, Lewis and Megerle found that when 15 mil thick free-standing films of EVA-based encapsulant were exposed to 150° C in a circulating air oven for 26 days, there was "very little yellowing." But at the same time tensile strength and elongation at break decreased significantly.[22,23] More recently Pern and Czanderna found that "Heating EVA in open vials at the same temperatures results in less yellowing at each temperature."

The above experiments, conducted in the presence of oxygen, suggested that simultaneously with deacetylation and formation of unsaturation, these unsaturated groups are being further oxidized leading to chain scission and crosslinking reactions and embrittlement of the EVA. However, Lewis and Megerle go on to add that "tear strength and elastic moduli at 10% and 100% elongations, which are within the regions of concern for PV use, remained relatively constant," and there was no effect on the electrical volume resistivities.

Lewis and Megerle's work suggests that a partially degraded EVA-based encapsulant with no significant degree of yellowing/browning may continue to function satisfactorily in flat plate PV modules.

At Springborn Laboratories, Inc. the contribution of U.V. to EVA yellowing at moderate temperatures has been further supported by our observation that in "browned modules" the EVA beneath the cells, where it is protected from U.V. exposure, has not exhibited discoloration and has retained most of its low tensile modulus and tensile elongation. It is also important to note that subsequent work under this PVMaT project failed to support conjugated unsaturation in the EVA polymer backbone as a mechanism for yellowing/browning of Eva-based encapsulant. Rather, this work provides strong support for a mechanism of yellowing/browning which involves an interaction of additives in the EVA-based encapsulant (see Sections 2 and 3 of this report for details).

1.2.2 Effects of U.V. Radiation:

Overview: Based on the literature reviewed, it appears that as with temperature, U.V. alone is not sufficient to induce significant degrees of yellowing/browning. However, when U.V. and temperature are combined, e.g. 85 to 90° C and above and one or more suns, and EVA-based encapsulant is exposed for extended periods of time, discoloration can be expected.

One of the first questions that needs to be asked is, what intensity and wavelengths of U.V. radiation are involved with PV Modules. Obviously we were concerned with radiation that strikes the earth's surface at various locations around the globe, and in designing an encapsulant we really needed to consider the "worst case" situations - those regions where light is most intense and the spectrum of U.V. wavelengths broadest, especially below 300 nm.

Conventional wisdom has it that little radiation below 300 nm reaches the earth surface, but in a joint meeting with module producers and SERI, it was indicated that there can be bursts of sunlight penetrating the atmosphere having wavelengths of 220 nm.[24] Of course, the "white" glass superstrate will filter out most of the radiation below approximately 280 to 285 nm.

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21 J. H. Wohlgemuth and R. C. Petersen, Photovoltaic Performance and Reliability Workshop, October 25-26, 1990, Lakewood, CO, Laxmi Mrig, (1990), p. 247-258.

22 K. J. Lewis and C. A. Megerle, Encapsulant degradation in photovoltaic modules, ACS Symp. Ser, 220, 387-406 (1983).

23 C. A. Megerle and K. J. Lewis, Encapsulant degradation in photovoltaic modules, Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.), 23, 250-1 (1982).

24 J. Galica, Internal Memorandum, Springborn Laboratories, Covering Meeting at SERI, Feb. 22, 1990, (Feb. 26, 1990).

Finally, H.W. Zussman claims that while the solar spectrum does not extend below 285 nm at sea level, radiation between 290 and 300 nm routinely falls on the earth's surface, and while relatively small in intensity, this band can do significant damage to resins sensitive to these wavelengths.[25]

Low ambient temperature: When minimodules were continuously exposed to RS-4 sunlamps at Springborn Laboratories, Inc. (nominal 1.4 UV suns) at 50° C, there was no visible change in the encapsulant after 35,000 hours of exposure[26]. It should be pointed out that the RS-4 radiation was directed through a pyrex filter, so all radiation below 275 to 280 nm was effectively eliminated.[27]

When Liang exposed EVA films (A9918) to a 450 watt medium pressure mercury lamp (6 to 10 suns; 295 - 380 nm) at 25° C, he found no significant change in molecular weight nor percent methylene chloride extractables.[28] But when Pern and Czanderna exposed both Elvax 150 and EVA (presumably fully formulated A9918) to RS-4 at 46° C for 237 hours, they observed increased cross-linking, the evolution of acetic acid, but no yellowing.[29] Since this work was conducted with free-standing films, photobleaching of the chromophoree may have been occurring.

Moderate ambient temperatures: When minimodules were exposed to 70° C temperature and natural sunlight (one sun at Enfield, CT using OPTAR racks, outdoor photothermal accelerated reactors) there was no visible change in the EVA-based encapsulant after 12,000 hours of total time on the OPTAR. At 90° C under the same conditions, the encapsulant showed "slight yellowing" after 12,000 hours, but not enough to degrade electrical performance.[30,31] When minimodules were exposed to 105° C and one-sun there was "moderate yellowing." Pern and Czanderna reported that when Elvax 150 and EVA (A9918) films were exposed to radiation from three RS-4 sunlamps at 87° C, "a light yellow color develops." "With one RS-4 present, a yellow color is detected."

1.2.3 Bleaching of discolored EVA-based encapsulant:

Overview: When a crack develops in the glass over previously exposed and browned EVA-based encapsulant, the color is removed in the immediate vicinity of the crack. When air in the combination with U.V. reaches the discolored material a "photobleaching" takes place. This has been seen by various investigators, and has been verified in the laboratory here at STR.

The phenomenon appears to be the same as that which prevents color formation between cells in modules and in proximity to the cell edge where air can diffuse in through the backing material. This process appears to be enhanced by heat but more notably by U.V. radiation.

Detailed findings: In 1983, Liang noted this bleaching effect in the laboratory. According to Liang, photothermal degradation of A9918 EVA, "...initially causes yellowing, i.e., increase in absorption at 400 nm and a greater rate of increase at 360 nm. This increase in absorption then causes accelerated photolysis which in turn leads to bleaching of these absorbing species. The result is attainment of a photostationary equilibrium in transmission at

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25 H.W. Zussman, Ultraviolet Absorbers for Stabilization of Materials and Screening Purposes, Modern Plastics Encyclopedia, September 1959, 37, 1A, p 372.

26 J.H. Wohlgemuth and R. C. Petersen, Photovoltaic Performance and Reliability Workshop, October 25-26, 1990, Lakewood, CO, Laxmi Mrig, (1990), P. 247-258.

27 Pyrex brand filter panes #7740 typically will transmit 1% at 278 nm, 5% at 285 nm, and 50% at 306 nm. (as required for ASTM G23 "Operating Light-Exposure Apparatus (Carbon-Arc Type) With and Without Water for Exposure of Nonmetallic Materials").

28 R. H. Liang, S. Chung, A. Clayton, S. Di Stefano, K. Oda and S. D. Hong et al., Photothermal degradation of ethylene/vinyl acetate copolymer, Polym. Sci. Technol, 20, 267-78 (1983).

29 F. J. Pern and A. W. Czanderna, AIP Conference Proceedings 268 Photovoltaic Advanced Research and Development Project, Rommel Noufi, (American Institute of Physics, New York, 1992), p. 445-451.

30 K. J. Lewis and C. A. Megerle, Encapsulant degradation in photovoltaic modules, ACS Symp. Ser, 220, 387-406 (1983).

31 J. H. Wohlgemuth and R. C. Petersen, Photovoltaic Performance and Reliability Workshop, October 25-26, 1990, Lakewood, CO, Laxmi Mrig, (1990), p. 247-258.

400 nm."[32] We might add that this equilibrium can shift more towards color-producing species or more towards colorless, fully oxidized EVA depending on the relative presence or absence of oxygen.

Pern and Czanderna demonstrated the bleaching of yellow-brown, field-discolored EVA by heating the material in air at 57° C for 120 to 150 hours. During this exposure, samples were subjected to radiation from either three RS-4 sunlamps, a 150-W Xenon light source, or a 150-W Xenon source that was focused and filtered to remove all radiation below 440 nm. In each case, the yellow color of the EVA as well as the absorbance decreased.[33]

1.2.4 Catalytic Effects of Acetic Acid:

Overview: There is evidence that acetic acid will catalyze the deacetylation of EVA copolymer at elevated temperatures. However, it is unclear if this same effect occurs at more modest temperatures, typical of normal module operating conditions, i.e., 50 to 100° C.

Laboratory investigations suggest that acedic acid may be contributing to corrosion of metallization, interconnects and solder joints, but observations of fielded modules do not support this.

Detailed findings: A principal by-product of thermolysis or photothermolysis of EVA copolymer is acetic acid, as discussed in section 2.2.1. Bubbles on the back side of discolored modules at Carrizo plains, "as well as those built by other manufacturers," suggested that EVA degradation results in evolution of a gaseous product.[34] Also, investigators who have dissected discolored modules from Carrizo Plains have noted the smell of acetic acid.

However, it should be pointed out that in some cases Springborn Testing & Research, Inc. found that bubbles in the backing film of fielded modules were located between plies of the laminated backing material and were obviously caused by residual solvent or other components of the laminating adhesive.

What effect, if any, does this acetic acid have on the further degradation of EVA, especially if the acid is trapped between two relatively impermeable layers, such as glass superstrate and foil backing material?

Sultan and Sörvik report that deacetylation rate of EVA copolymers increases with increasing vinyl acetate content, and they attribute this phenomenon to increased amounts of block sequences and "an enhanced acid catalytic effect."[35]

When Razuvaev et. al. conducted isothermal studies of a 33% vinyl acetate containing EVA copolymer at 260° C, they noted that the thermolysis was "strongly catalyzed by $SnCl_2$, HCl, and to some extent evolved HAC." They also observed that inhibitors of radical reactions did not affect the rate of deacetylation.[36]

A major U.S. module manufacturer indicated that when it subjected the formulated EVA A9918 to RS-4 sunlamp at 90° C with the encapsulant sandwiched between two glass plates, discoloration occurred in only five weeks. The trapped acetic acid evolved is thought to be "autocatalytic for decomposition."[37]

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32 R. H. Liang, S. Chung, A. Clayton, S. Di Stefano, K. Oda and S. D. Hong et al., Photothermal degradation of ethylene/vinyl acetate copolymer, Polym. Sci. Technol, 20, 267-78 (1983).

33 F. J. Pern and A. W. Czanderna, AIP Conference Proceedings 268 Photovoltaic Advanced Research and Development Project, Rommel Noufi, (American Institute of Physics, New York, 1992), p. 445-451.

34 J. Schaefer, L. Schlueter, A. Rosenthal, H. Wenger and A. E. Luque, Electrical degradation of the Carrizo Plains power plant, E. C. Photovoltaic Sol. Energy Conf., Proc. Int. Conf., 10th, P1248-53, (1991).

35 B. A. Sultan and E. Sörvik, Thermal degradation of EVA (ethylene-vinyl acetate copolymer) and EBA (ethylene-butyl acrylate copolymer) - a comparison. II. Changes in Unsaturation and Side Group Structure., J. Appl. Polym. Sci, 43, 1748-59 (1991).

36 G. A. Razuvaev, B. B. Troitskii, L. V. Chochlova and Z. B. Bubova, Polymer Letters, 11, 512-523 (1973).

37 R. A. White, Internal Memorandum, Springborn Laboratories, (August 8, 1991).

Pern and Czanderna subjected several different cured EVA-based encapsulation formulations, including A9918, 15295, 16718A, and 18170, to heat only - no U.V. Samples were placed in capped vials and heated at 87°, 100°, and 130° C for 240 hours. Half had acetic acid vapor introduced into the vials; the other half did not.[38] They report that greater yellowing occurred in the acid containing vials, and attribute this to "acetic-acid-catalyzed yellowing."

Some investigators have noted corrosion of metallization and interconnects in degraded EVA-encapsulated modules from the field, and have speculated that the corrosion was created by acetic acid from degraded EVA which lead to fill factor degradation in some modules. However, when Solarex immersed cells in 50% aqueous acetic acid in the lab for 5,390 hours, there was no loss in conductivity of the silver bus and no metal corrosion.[39]

In addition, Solarex exposed cells to acetic acid vapors by sealing them inside polyethylene bags which contained open beakers of 50% acetic acid. After 3,550 hours of exposure at room temperature, there was no evidence of corrosion of cell metallization, but the tin-lead solder did corrode.

Solarex also pointed out that "none of the modules from the field, including Carrizo modules, show any visible corrosion of the front interconnects or solder joints." They concluded that "acetic acid corrosion does not appear to be the mechanism causing the fill factor degradation."

1.2.5 Effects of Metal and Metal Oxide Interfaces: Over the years several investigators have noted browning of EVA-based encapsulant over the contact grid lines of cells in flat plate modules.[40,41,42] This phenomenon has been distinguished from more general discoloration of EVA-based encapsulant which appears to proceed from the glass/resin interface inward. As one module manufacturer has pointed out, with grid-line browning, the grid lines appear dull and brownish while areas over the ribbons, generally tin-plated copper, remain water-white and the ribbons appear shinny.

Also, grid-line browning is reported to take place at the metal/encapsulant interface and proceed outward. Solarex, for example, reported that when EVA-based encapsulant was stripped from the surface of a fielded module which had exhibited this grid-line browning, the yellow color remained on the silver metallization, and there was "no sign of this yellow in EVA."[43]

Megerle and Lewis reported that, "When browned EVA, protected by Tedlar, was peeled from the metallization of a cell in an oven aged module, the tear surface on the EVA film showed only a minor amount of oxidation, similar to that observed on EVA tear surfaces which had not been in contact with the metallization. Analysis of the corresponding metallization surface, on the other hand, showed that several hundred nanometers of heavily oxidized polymer remained behind on the metallization surface after the tear. This suggests that the oxidation of the polymer initiated at the interface between the metallization and the polymer, and a reaction front proceeded through the polymer as the catalyzed oxidation progressed. When the polymer was peeled from the cell, the tear occurred along this reaction front." [44]

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38 F. J. Pern and A. W. Czanderna, AIP Conference Proceedings 268 Photovoltaic Advanced Research and Development Project, Rommel Noufi, (American Institute of Physics, New York, 1992), p. 445-451.

39 J. H. Wohlgemuth and R. C. Petersen, Photovoltaic Performance and Reliability Workshop, September 16-18, 1992, Golden, CO, Laxmi Mrig, (1992), p. 313-326.

40 K. J. Lewis and C. A. Megerle, Encapsulant degradation in photovoltaic modules, ACS Symp. Ser, 220, 387-406 (1983).

41 C. A. Megerle and K. J. Lewis, Encapsulant degradation in photovoltaic modules, Polym. Prepr. (Am. Chem. Soc., Div. Polym. Chem.), 23, 250-1 (1982).

42 F. J. Pern and A. W. Czanderna, Solar Energy Materials and Solar Cells, Characterization of Ethylene Vinyl Acetate (EVA) encapsulant: Effects of Thermal Processing and Weathering Degradation on its Discoloration, (Elsevier Science Publishers, 1992).pp. 3-23.

43 J. H. Wohlgemuth and R. C. Petersen, Photovoltaic Performance and Reliability Workshop, September 16-18, 1992, Golden, CO, Laxmi Mrig, (1992), p. 313-326.

44 C. A. Megerle and K. J. Lewis, Encapsulant degradation in photovoltaic modules, Polym. Prepr. (Am.

Lewis and Megerle observed this grid line browning as early as 1983.[45] Since grid-line metallization uses transition metal oxide-containing glass frit, as well as silver, they speculated that discoloration at the grid lines was being catalyzed by one or more of these materials.

To confirm this hypothesis, Lewis and Megerle added 1 to 10% of each of various metal oxides to a lead borosilicate glass matrix, and encapsulated samples of these glasses in panels using EVA. When these test modules were oven aged and monitored for browning, it was observed that EVA over those glass samples containing vanadium oxide, antimony oxide, or a mixed copper/nickel oxide showed accelerated browning.

It was also observed that "certain primers" had the ability to retard browning when applied to "solar cell contacts" prior to encapsulation.

Since that time, Pern and Czanderna have also studied the effect of metals on accelerated discoloration of EVA-based encapsulants. They added silver, copper, lead, and tin to EVA-based formulations A9918 and 18170 via metal acetates, and then heated the specimens in an oven for 264 hours at 85° C. They reported, "EVA turned yellow-brown in 24 h with Ag+, pale greenish yellow in 264 h with Cu++, and did not discolor with Pb and Sn ions."[46]

They concluded that EVA-based encapsulant discoloration is catalyzed by these metals and in the following order of activity: Ag+ > Cu++ >> Sn 4+, Pb++.

1.2.6 Effects on Crosslinking of EVA: In 1983, R.H. Liang et. al. subjected samples of encapsulant film, formulation A9918, to roughly 6 to 10 U.V. suns (295 to 380 nm) from a 450 watt medium pressure mercury lamp. At 85° and 105° C, Liang indicates that, "Apparently EVA undergoes chemical crosslinking when it is subjected to photothermal aging which result in a decrease in the proportion of the extractables and in apparent modulus, and an increase in the chemical crosslinking density."[47]

When Pern and Czanderna determined gel content, a measure of degree of cross-linking, of cured but unaged strips of EVA-based encapsulant by THF extraction, they reported values of 68 to 71%.[48] This is in good agreement with the gel content recommended by STR, which is a minimum of 60% but preferably 80% or above. It should be noted that gel content is influenced significantly by the lamination and curing cycle used during module manufacture.

However, when Pern and Czanderna evaluated EVA-based encapsulant over cells of field-aged modules, they found a gel content of 85 to 88% "around the cell edges" and 90 to 92% in the yellowed region directly over the cells. This suggests that a significant amount of crosslinking has taken place as a result of photooxidative degradation.

1.2.7 Effect on additive levels in EVA-based encapsulant: When R.H. Liang et.al. subjected EVA films (A9918) to the U.V. of a 450 watt medium pressure mercury lamp (reportedly 6 to 10 U.V. suns) at room temperature they found an insignificant effect on additive levels.[49,50] Using high pressure liquid chromatography, they followed the

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Chem. Soc., Div. Polym. Chem.), 23, 250-1 (1982).

45 K. J. Lewis and C. A. Megerle, Encapsulant degradation in photovoltaic modules, ACS Symp. Ser, 220, 387-406 (1983).

46 F. J. Pern and A. W. Czanderna, AIP Conference Proceedings 268 Photovoltaic Advanced Research and Development Project, Rommel Noufi, (American Institute of Physics, New York, 1992), p. 445-451.

47 R. H. Liang, S. Chung, A. Clayton, S. Di Stefano, K. Oda and S. D. Hong et al., Photothermal degradation of ethylene/vinyl acetate copolymer, Polym. Sci. Technol, 20, 267-78 (1983).

48 F. J. Pern and A. W. Czanderna, Solar Energy Materials and Solar Cells, Characterization of Ethylene Vinyl Acetate (EVA) encapsulant: Effects of Thermal Processing and Weathering Degradation on its Discoloration, (Elsevier Science Publishers, 1992).pp. 3-23.

49 S. Di Stefano and A. Gupta, Photocatalytic degradation of a crosslinked ethylene-vinyl acetate (EVA) elastomer, Polym. Prepr., Am. Chem. Soc., Div. Polym. Chem, 21, 178-9 (1980).

effect of U.V. radiation on the phenylphosphite ester antioxidant (Naugard-P) and 2-hydroxy-4-n-octyl benzophenone U.V. absorber (Cyasorb UV531) levels. After 1400 hours of irradiation, the additive levels were essentially unchanged. However, there was "efficient removal of residual curing agent" (Lupersol 101) after only about 60 hours of exposure.

But at increased temperatures there was a significant change. At 70° C and with the same U.V. exposure, there was steady weight loss up to 0.5% after 500 hours, which the authors equate to 2 years of outdoor conditions. A 1% weight loss was observed after 800 hours at 80° C, and roughly 1.5% was lost with the sample open to the air after 800 hours at 105° C.

While some of the weight loss is attributed to the formation of volatile photooxidative degradation products, such as acetic acid, Liang indicates that a portion of this weight change was due to loss of additives. Unfortunately, no further analytical work was done to quantify the loss of additives, either individually or collectively.

It is noteworthy, that analytical work under this PVMaT project showed a loss of both UV-531 and Tinuvin 770 with exposure to Xenon-Arc (nominal two suns) at 100° C (see section 3 of this report for details), which corroborates the following study. Here, we speculate that loss involves chemical rearrangement of the additives to nonabsorbing species rather than exudation or volatilization.

Using UV-visible spectroscopy, Pern and Czanderna investigated the residual Cyasorb UV-531 levels in a number of "virgin cured EVA, aged but unexposed EVA (stored in dark for 6 years) and EVA degraded for various times in field-deployed PV modules." The results are shown in the following figure 1.[51]

F.J. Pern, A.W. Czanderna / Ethylene vinyl acetate encapsulant

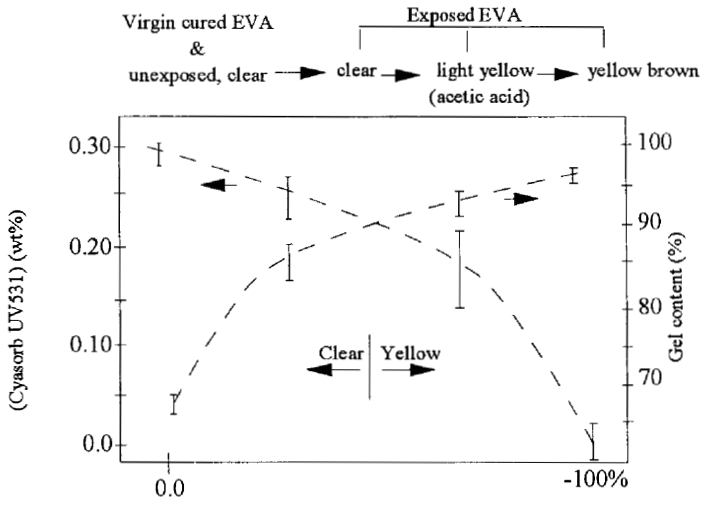

Figure 1 - Arbitrary Extent of EVA Degradation (%)

The Cyasorb UV-531 concentration values range from 0.3% (original concentration) for virgin EVA-based encapsulant, through 0.18 to 0.22% for light yellow exposed encapsulant, to 0 to 0.02% for browned material. The Cyasorb concentration of the 6-year aged but unexposed sample was essentially unchanged.[52]

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50 R. H. Liang, S. Chung, A. Clayton, S. Di Stefano, K. Oda and S. D. Hong et al., Photothermal degradation of ethylene/vinyl acetate copolymer, Polym. Sci. Technol, 20, 267-78 (1983).

51 F. J. Pern and A. W. Czanderna, Solar Energy Materials and Solar Cells, Characterization of Ethylene Vinyl Acetate (EVA) encapsulant: Effects of Thermal Processing and Weathering Degradation on its Discoloration, (Elsevier Science Publishers, 1992).pp. 3-23.

52 F. J. Pern and A. W. Czanderna, Solar Energy Materials and Solar Cells, Characterization of Ethylene

When Pern and Czanderna exposed cured encapsulant film to DSET 1500W Xenon light filtered by a plate of glass, they reported roughly a 10% loss in Cyasorb UV531 concentration after 900 hours. Temperature was not indicated, but is assumed to have been 60° C.[53]

Thermal loss of Cyasorb at 57° to 60° C was said to be "insignificant." This fact supports our speculation that "loss" involves chemical rearrangement to a nonabsorbing compound.

1.2.8 Probable Mechanisms: Acetic acid is the principal product of decomposition when EVA copolymer is heated at elevated temperatures.[54,55,56,57] Lesser quantities of chain fragments as well as ketene, carbon monoxide, carbon dioxide, and water have also been noted. The latter products are thought to be formed from further thermal decomposition of the evolved acetic acid.

Photothermolysis is thought to proceed in a similar manner. Andrei and Hogea have proposed a mechanism that is in agreement with the work of several other investigators. This mechanism comprises a transition stage, with the formation of a six membered ring, leading to the formation of double bonds and evolution of acetic acid.[58,59,60]

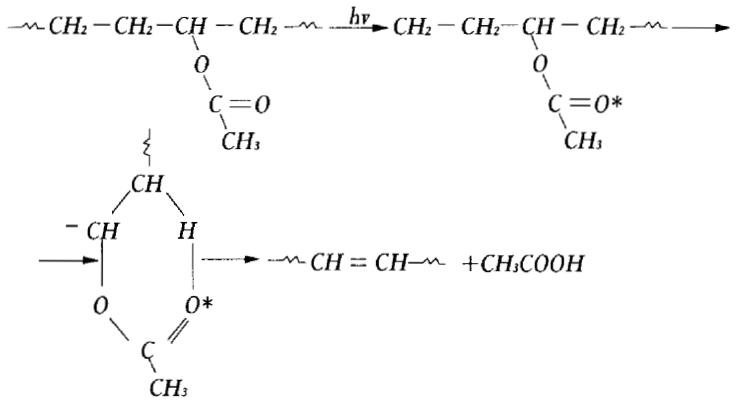

Figure 2 - Proposed Mechanism for EVA Deacetylation

Since EVA copolymers were thought to contain small quantities of vinyl acetate homopolymer blocks, photolysis of the acetate groups followed by formation of polyene or conjugated unsaturated groups was postulated in the development of a yellow to brown color. With a vinyl acetate group in every repeating unit of the block - that is every other carbon in the chain - photolysis was thought to result in sequences of alternating double and single

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Vinyl Acetate (EVA) encapsulant: Effects of Thermal Processing and Weathering Degradation on its Discoloration, (Elsevier Science Publishers, 1992).pp. 3-23.

53 F. J. Pern, Photovoltaic Performance and Reliability Workshop, September 16-18, 1992, Golden, CO, Laxmi Mrig, (1992), p. 327-344.

54 B. A. Sultan and E. Sörvik, Thermal degradation of EVA (ethylene-vinyl acetate copolymer) and EBA (ethylene-butyl acrylate copolymer) - a comparison. I. Volatile decomposition products, J. Appl. Polym. Sci, 43, 1737-45 (1991).

55 G. A. Razuvaev, B. B. Troitskii, L. V. Chochlova and Z. B. Bubova, Polymer Letters, 11, 512-523 (1973).

56 P. Bataille and B. T. Van, Journal of Thermal Anal., 8, 141-153 (1975).

57 I. K. Varma and R. K. Sadhir, Angew. Makrom. Chem., 40, 1-10, 11-21 (1975).

58 C. H. Andrei, I. Hogea, and V. I. Dobrescu, Photodegradation and photostabilization of the ethylene-vinyl acetate copolymers. I. Aspects of the mechanism of photodegradation reactions, Rev. Roum. Chim, 30, 865-73 (1985).

59 D. H. Grant and M. Grassie, Trans. Faraday Soc., 56, 445 (1960).

60 G. Geuskans, M. Borsusi and C. David, Europ. Polym. J., 8, 883 (1972).

bonds in the chain. Such conjugated double bonds are known to develop color, with degraded polyvinyl chloride being a notable example.[61]

The presence of vinyl acetate blocks is supported by U.V. spectroscopy work by Gardner and McNeill.[62,63] They report that an EVA copolymer with 12% vinyl acetate had 18.6% of its vinyl acetate groups in blocks of two and 3.6% in triads or longer sequences. We would expect that Elvax 150, with its comparative high 33% vinyl acetate content, would tend to have even greater proportions of the vinyl acetate groups occurring in triads or longer sequences.

Of course, these double bonds within the chains then are susceptible to further photooxidative degradation leading to chain scissioning and crosslinking by mechanisms that are well known for polyolefins.

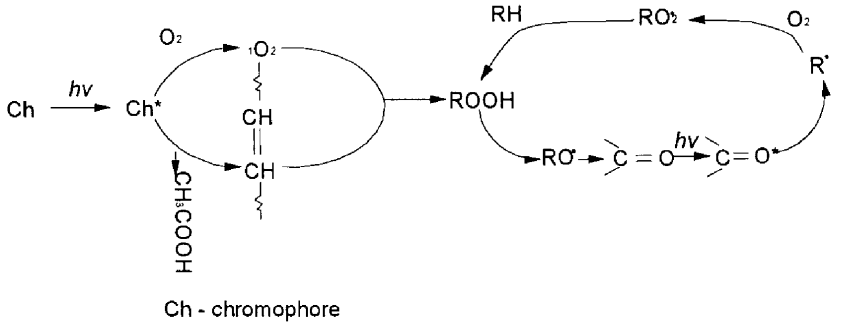

Figure 3 - Photoxidation of Polyolefins

However, extensive analytical work under this PVMaT project has revealed: 1 - no measurable loss of acetate groups from exposed EVA-based encapsulant, even severely browned material, 2 - no evidence of unsaturation in the polymer, let alone polyenes, and 3 - strong correlational and analytical evidence to support a mechanism of additive interaction rather than polyenes as the source of browning (see sections 2 and 3 of this report for details). It should be noted, that the above observations apply to EVA exposed to normal module operating conditions (i.e., 2 suns or less and temperatures less than 100° C). It has been well documented that thermolysis of the acetate group does not occur at elevated temperatures, not relevant to module operation (e.g. 130 to 150° C) as detailed in section 1.2.1 of this report.

1.3 Alternative Low Cost Encapsulation Materials

During the original work performed by Springborn Laboratories, Inc. under contract[64] to JPL, several alternative materials were investigated as encapsulants for photovoltaic cells. The initial screening criteria for the ideal encapsulation material included characteristics presented in Table 1. The fabrication processes for specific materials investigated in this work were either liquid casting or vacuum lamination.

A survey of materials was conducted during the JPL work, and findings were organized by price category. Polymers identified included polyvinyl chloride (PVC) homopolymers and copolymers, polystyrene, polyolefin homopolymer and copolymers, polyesters, polyvinyl alcohol, ionomers, acrylics, polyamides, cellulosics,

61 Encyclopedia of Polymer Science and Engineering, (Wiley-Interscience, New York, 1988).pp. 145-154.

62 B. A. Sultan and E. Sörvik, Thermal degradation of EVA (ethylene-vinyl acetate copolymer) and EBA (ethylene-butyl acrylate copolymer) - a comparison. I. Volatile decomposition products, J. Appl. Polym. Sci, 43, 1737-45 (1991).

63 D. C. Gardner and I. C. McNeill, J. Therm. Anal., 1, 300-407 (1969).

64 Willis, P.W., Investigation of Test Methods, Material Properties, and Processes for Solar Cell Encapsulants, Jet Propulsion Laboratory, JPL Contract 95427, Final Report, August 1986.

polyurethanes, and silicones, among others. From this survey, possible candidates were further reduced, based upon optical transparency, modulus, processability, and material cost. Final candidates selected for further development included two types of liquid casting resins, polymerizable butyl acrylate syrups and aliphatic urethanes, and two lamination polymers, ethylene vinyl acetate copolymer (EVA) and ethylene methyl acrylate copolymer.

The main purpose of liquid system development was to offer module manufacturers a processing option other than vacuum lamination. A final stabilized butyl acrylate system was formulated to produce a transparent low modulus rubber which was found suitable as a pottant material. However, major objections to the use of this material were the pungent odor of the monomeric butyl acrylate which requires good ventilation when handling, and the high exotherm which results from the high heat of polymerization during cure.

Table 1 - Encapsulant Material Specifications (a)

1	Glass transition temperature (Tg)	<-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 psi 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 compatibility	Compatible with automated cell handling and encapsulation equipment
16	Cost	As low as possible

(a) Willis, P.W., Investigation of Test Methods, Material Properties, and Processes for Solar Cell Encapsulants, Jet Propulsion Laboratory, JPL Contract 95427, Final Report, August 1986.

A two part aliphatic polyurethane system was also developed with assistance from Development Associates, Inc., a supplier of liquid urethane systems. The water white developmental material demonstrated resistance to UV degradation in the laboratory. Inadequacies with this system included poor bond strengths to substrates other than glass and limited pot life of the mixed two part system, i.e. 15 minutes. Primers for improved bond strengths were available from the manufacturer, but this system was not pursued to commercial status during the JPL program.

Of prime choice in the JPL-funded development work were lamination systems based upon Elvax 150 (DuPont) EVA having a 33% vinyl acetate content and 43 gm/10 min melt index. This resin was formulated to be cured in place during module lamination and further formulated for outdoor use. The current commercially available lamination encapsulants sold by Springborn Testing & Research, Inc. and others, are based upon this technology. Elvax 3185 is the same compositionally as Elvax 150 but is made to more exacting standards.

The second lamination formulation was based upon ethylene methyl acrylate copolymers (EMA) from Chevron Chemical Co. (formerly Gulf Oil Chemicals Co.). This system was not commercialized in lieu of the satisfactory laboratory and field results achieved with EVA-based system as the primary encapsulant material. However, from laboratory work conducted with EMA, it appears that these systems process similarly to EVA-based formulations. Furthermore, EMA may be found to demonstrate comparable or improved final product properties when compared with the Elvax 150-based encapsulant, e.g. higher thermal stability and creep resistance at lower gel contents.

Alternative resin system(s) with equivalent properties, but better overall outdoor stability were thought to be one possible solution to eliminate discoloration which occurs with EVA-based encapsulants. For example, studies have shown that ethylene n-butyl acrylate (EBA) copolymer is more thermally stable than EVA[65]. In this work, significant levels of decomposition product in the form of acetic acid were detected at the pyrolysis temperature of 150° C whereas the EBA was found to produce small amounts of butene, the main degradation product, after 30 minutes at 280° C.

Since the completion of development work with JPL, several new grades of ethylene copolymers have become commercially available. These new resins along with EMA formulations developed but not fully tested during the JPL program are of potential interest as alternative encapsulant materials. Alternative materials investigated included those which process using similar lamination techniques to the currently used EVA-based encapsulant system. Atochem, for example, produces a grade of EBA which has a 35% comonomer content and 40 gm/10 min melt index.

Prime candidate material types considered include:

* Ethylene n-Butyl Acrylate Copolymer (Quantum, Atochem)

* Ethylene Methyl Acrylate Copolymer (Exxon, Chevron, Atochem)

* Ethylene/Ethyl Acrylate Copolymer (Custom made - Atochem)

Other materials investigated include:

* EVA Maleic (acid or anhydride) Terpolymer; Carboxylated EVA (DuPont Bynel)

* Ionomers (DuPont Surlyn, Allied)

* Ethylene/Methacrylic Acid Copolymer (DuPont Nucrel)

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65 Sultan, Bernt-Åake; Sörvik, Erling (Dep. Polym. Technol. Chalmers Univ. Technol. S-412 96 Göteborg Swed). Thermal degradation of EVA (ethylene-vinyl acetate copolymer) and EBA (ethylene-butyl acrylate copolymer) - a comparison. I. Volatile Decomposition Products. J. Appl. Polym. Sci; 1991; 43: 1737-45.

Specific grades of commercially available alternative copolymers were identified, and the basic properties summarized in Task 4 of the current NREL program. This information was obtained by contacting the above manufacturers directly and searching the "materials" computer databases such as Plaspec and Materials Selector. From this tabulation, samples of the most promising grades of materials were procured.

Light transmission spectra was measured on compression molded films and bulk costs on each investigated. Initial development work was conducted on those systems whose optical clarity, properties, and processing characteristics are similar to those of the commercial EVA encapsulant.

Of course, if the alternative candidate materials were pursued further, they would have to be fully screened to identify any other potential problems associated with these materials. It is understood that any new polymer system would also require extensive testing to prove its performance in PV applications (Tasks 7,8, and 9).

All preliminary evaluations compared the material behavior to that of Elvax 150 EVA based encapsulant currently used in the PV modules. This work was carried out concurrently with Task 4 - "Enhance EVA Formulation".

1.4 Accelerated U.V. Aging Methods

An investigation was undertaken to compare and evaluate various artificial UV aging systems available for aging EVA samples with the goal of selecting the most suitable apparatus for future work on this PVMaT program. One objective of the aging work is to reproduce the yellow/brown color change of the EVA encapsulant as seen in the field, but in a much shorter time frame. Furthermore, it is also our concern to choose a method that closely simulates the spectral output of sunlight in order to reproduce "realistic" degradation processes.

Manufacturers of commercially available UV weathering equipment, Atlas Electric Devices Co., Heraeus DSET Laboratories, Inc., and Q-Panel, were contacted for information and equipment details. In addition, telephone calls were placed to bulb manufacturers including GE, Sylvania, Hanovia, American Ultraviolet Co., Superior Quartz, Jelight Company, Ultraviolet Resources International, Apollo Lighting, and North American Philips Lighting Corporation in search of commercially available bulbs that emit UV light in both the UVB (280 - 320 nm) and UVA (320 - 400 nm) ranges. Information gathered on the light sources in general and equipment/bulbs in specific is highlighted below:

XENON ARC SYSTEMS

* The spectral irradiance of the filtered (borosilicate/borosilicate or quartz/borosilicate) Xenon lamp in the UV - visible range most closely resembles the spectral output of natural sunlight of any of the systems investigated, and includes the low (280 - 300 nm) wavelengths of interest.

* The Xenon lamp spectra does not contain large "spikes" as do spectra of other sources, i.e., RS-4 bulbs, Sunshine Carbon Arc.

* Atlas Electric and DSET Heraeus both make several models of Xenon weathering equipment with controlled irradiance for improved reliability of weathering results. The equipment identified includes:

* Xenon Arc Weather-O-Meters/Fad-O-Meters
  Atlas C-series: Ci3000,Ci35, Ci65
  Atlas SunChex (benchtop model)
  DSET Xenotest CPS 1200
  DSET Suntest CPS (benchtop model)

CARBON ARC SYSTEMS

* The spectral output of the Sunshine Carbon ARC has extremely large spikes in the 350 to 450 nm range which are not found in natural sunlight. This alone makes this system suspect for unrealistic weathering findings/degradation when compared to natural outdoor exposure.

* The "testing community" is moving away from carbon arc to the preferred Xenon Arc accelerated test methods.

* This light source was not considered further as an option for UV aging in lieu of the alternative, more promising light sources, e.g. Xenon.

FLUORESCENT UV MERCURY BULBS

* American Ultraviolet has 40 watt Westinghouse fluorescent sunlamp bulbs which can be used in a standard 4-bulb fluorescent light fixture. It would be necessary to operate one UVB and one UVA fluorescent together in order to properly simulate the significant UV range. The problem with this set-up would be that in order to get a uniform mixture of both UVB and UVA light, the test specimens would have to be at least 12 inches away. Considering that the total wattage of the bulb system would be 160 watts, the testing would take a long time. Ultraviolet Resources International has similar UVB and UVA fluorescent bulbs.

* The UVA bulbs do not emit down below 295 nm whereas the UVB bulbs emit much lower (beginning around 275nm). It is speculated that the primary wavelength range responsible for EVA degradation lies somewhere between 285 and 295 nm. However, it would not be wise to assume that other higher wavelengths do not solely or synergistically contribute to the browning. Therefore, such bulbs as the UVA or UVB are not the best choice for this investigation unless a combination of bulbs in a single apparatus could be used.

* Both Atlas (UVCON) and Q-Panel (Q-U-V) sell weathering cabinets which use fluorescent UVA and UVB bulbs. As the names state, these low wattage bulbs emit most all of their energy in the UV range of the spectrum. However, in both weathering cabinets, only one type of bulb can be used at a time - either UVA or UVB.

* At present, use of combined bulbs does not appear to be a commercially available option.

MERCURY VAPOR AND SUN TANNING BULBS

* One practice for artificial UV weathering in the past was to expose plastic samples to a Mercury Arc lamp (discontinued ASTM D795, Exposure of Plastics to S-1 Mercury Arc Lamp). The S-1 lamp (400 W) and the more recent RS-4 (100 W) lamp were made by GE. STR has several RS-4 test chambers made by Test Lab Apparatus, Inc. which were used in numerous aging studies in the past, including the JPL-funded solar encapsulant work. However, ASTM D795 was discontinued some time in the early 1980's and the production of RS-4 bulbs were recently discontinued by GE. Therefore, the search for alternative sources of Mercury Vapor and Sun tanning bulbs were investigated as one possible aging scheme for this program.

* GE, Superior Quartz, American Ultraviolet, and North American Philips Lighting Corp. specialize in medium pressure mercury bulbs. Sylvania manufactures mercury high intensity discharge lamps and Jelight Company specializes in low pressure mercury bulbs. GE and Sylvania have discontinued production of the RS type sun tanning bulbs. The RS sun tanning bulbs, formerly made by GE, were used for accelerated UV aging of plastics. North American Philips imports a metal halide bulb.

* Sylvania makes 400 watt high intensity discharge mercury lamps. These lamps have a glass outer tube which cuts off all wavelengths below 300 nm. The principal wavelengths generated by these bulbs are in the visible spectrum, however there are ultraviolet wavelengths generated at 334.2 nm and 365 nm.

* GE makes a series of short arc mercury bulb, designated HBO series, which has a peak wavelength at 360 nm and cuts off at 270 nm. This series bulb is supplied at 50, 200, and 500 watts and requires a special power supply to operate.

* American Ultraviolet has a medium pressure mercury bulb that appears to be similar to the GE HBO series. The Portacure 1000 energy spectral distribution emits approximately 15 relative units of energy in the 280 - 300 nm range and approximately 100 relative units at 380 nm. This bulb requires a special power supply.

* Superior Quartz is a specialty bulb manufacturer specializing in custom medium pressure mercury bulbs. It is possible that they could custom manufacture the RS-4 bulb, but they generally do not manufacture "R40"-shaped bulbs.

* Jelight Company manufactures low pressure mercury vapor lamps. The low pressure mercury bulbs generate most of their energy at 250 nm or below and comparatively little at 282, 302, 313, 365, 404, 436, and 546 nm.

* North American Philips has a 400 watt metal halide bulb that emits light from 275 nm to 380 nm and appears to have a more uniform spectral distribution than the discontinued RS-4 bulb. The HPA400 metal halide bulb is approximately 4.2" x 0.7" and has a special ballast that must be used. One possible drawback to this bulb is its 350° C temperature.

* Mercury vapor and/or sun tanning bulbs emit UV light. However, the spectral emission is considered to be "spiky".

* Many commercially available bulbs have a filter (the outer glass itself) which may filter out the harmful UVB wavelengths which are of interest in our work.

* There are no commercial aging devices employing these bulbs. We would need to purchase a ballast, and to design chambers in which to run our tests. Since we have no data on the ability of a home made "box" to degrade the EVA, it would not be prudent to rely solely on this method. Reliability and reproducibility of a custom made system is questionable.

Conclusions

* The fluorescent UV bulbs are lower wattage, less expensive, and do not require a separate filter - the glass on the bulb itself is the filter. However, their spectral output is limited to a small portion of the UV range and may yield unrealistic results in exposed samples.

* Since there are no commercial aging devices employing Mercury vapor and/or sun tanning bulbs, we would need to purchase a ballast and to design chambers in which to run our tests. Since we have no data on the ability of a home made "box" to degrade the EVA, it would not be prudent to rely solely on this method. Concerns of reliability and reproducibility once again come into play. Perhaps this less expensive system could be used as a secondary screening tool, keeping in mind its limitations.

* Since the objective of our work is to find a suitable accelerated aging scheme which causes the encapsulant to discolor and simulates outdoor conditions, the best lamp source for our purpose is the Xenon lamp. There has been extensive research on Xenon weathering systems, and there is equipment available which has been refined to adjust for variations in irradiance and other critical factors.

* If the encapsulant program progresses to where we are concerned about water/moisture absorption, we would have the added ability to run humidity in the C-series and Xenotest Weather-O-Meters to simulate hot/humid regions and other combinations.

* The benchtop Xenon models have limitations of size and flexibility. Of the two reviewed, the Atlas Sunchex and DSET Suntest, the latter appears to be a much better quality piece of equipment with controlled irradiance.

* Of the Xenon systems, the favored full-size units are the Atlas Ci35 and the DSET Xenotest 1200 CPS. While the Ci65 was preferred technically, the Ci35 and 1200 CPS were more economical.

1.5 Survey on Discoloration of EVA-Based Encapsulants for PV Modules

1.5.1: The objective of this survey was to investigate case histories of fielded EVA encapsulated photovoltaic modules in an effort to make correlations between encapsulant discoloration and various material, fabrication, placement, and exposure parameters.

1.5.2: Scope - Survey participants were selected from the industry based on a minimum 4 year history of fielded, EVA- encapsulated, photovoltaic modules. Information was obtained from both module manufacturers and module test facilities. Participants included: Advanced Photovoltaic Systems, Inc., Arizona Public Service, ENDECON, Florida Solar Energy Center, Global Photovoltaic Specialists, Inc., PG&E, Photocomm, Inc., Sandia National Laboratories, Siemens Solar Industries, SMUD, Solar Web, Inc., Solarex, Solec International, Inc., Southwest Regional Experimental Station (SWRES), Texas Instruments, United Solar Systems Corp., US Navy China Lake, and Utility Power Group, Inc.

The survey was introduced by a brief telephone interview of potential participants. This interview established a suitable contact and determined whether there was a history of EVA-based encapsulant use. Once a reasonable history was discovered, a written questionnaire (refer to Appendix 3) was sent to key individuals. The questionnaire asked detailed questions about module construction, processing, field placement, and operation. As necessary, the written survey was followed by a telephone conversation or meeting in which the survey answers were discussed in more depth. Supplementary information was also obtained from individuals active in the photovoltaic community. Site visits were arranged in order to obtain comparative data from manufacturer/to/manufacturer and test-site/to/test-site.

1.5.3 Results - A brief outline of survey results appears in Table 2. The survey uncovered incidences of EVA encapsulant discoloration after exposure periods ranging from 4 to 10 years. It should be stressed that the dates reported for discoloration of the EVA do <u>not</u> necessarily reflect discoloration at its inception. The reported dates, rather, describe the point at which discoloration was first realized. Very often discoloration was not noticed until its advanced stages. The rate of discoloration for most modules could not be determined definitively because of a lack of documentation and quantitative browning measurements.

It should also be noted that information provided by the module manufacturer and testing facility is sometimes contradictory. Contradictions were due, in part, to the fact that testing facilities often did not report key observations to the manufacturer. For example, Table 2 information provided by Manufacturer "E" reported a ten year history of module operation in the Mohavi Desert without discoloration of the EVA-based encapsulant. At the same time, there was a contradicting report of Manufacturer "E" which described browned modules after 5 years exposure at China Lake (in the Mohavi Desert).

In most cases, there was concrete information provided with respect to: EVA-based encapsulant source, EVA-based encapsulant formulation, and construction/design of the modules. Information provided on discoloration of the modules, however, was often too subjective to enable a direct comparison from one testing facility to the next, and the onset of browning was generally not realized until it was quite advanced.

Table 2 - The History of Fielded, EVA- Encapsulated PV Modules

Observation Location	Mfg.	EVA Source	Formulation	Color	Approx. Max.[66] Temperature	Time	Construction [67]	Elevation
SWRES Las Cruces, NM	A	-	A9918	brown	-	3-4 years	-	1198 m
Hawaii	B	a	A9918P	**clear**	-	4 years	B	-
Detroit	B	a	A9918P	**clear**	-	4 years	B	191 m
California	B	a	A9918P	**clear**	-	4 years	B	-
San Ramon, CA	C	b	other	brown	64C[68]	4-5 years	B	8 m
Davis, CA	D	c	A9918	brown[69]	-	4-5 years	D	8 m
China Lake, CA	A	-	A9918	discolored	-	5 years	A?	-
China Lake, CA	E	a	A9918	brown	-	5 years	-	681 m
Sells, AZ	C	b	other	80% brown	-	6-8 years	B	-
City of Austin, TX	C	b	other	slight brown	60-71C[(3),70]	7 years	B	250 m
SMUD, CA	D	c	A9918	light amber	65C[71]	7 years	B	8 m
Caples Lake, CA	C	b	other	**clear**	52C[72]	> 7 years	B	2400 m
Carrizo Plains, CA	C	b	other	slight brown	-	8 years	B,D	640 m
John Long, Phoenix, AZ	C	b	other	moderate	77C[(3)]	8 years	B	340 m
Sandia, Albuquerque, NM	D	d	A9918	light amber	-	8 years	B	1619 m
SMUD, CA	C	b	other	slight brown	77C[(3)]	9 years	B	10 m
San Ramon, CA	F	c	A9918P	**clear**	-	9-10 years	B	8 m
Carrizo Plains, CA[73]	C	b	other	dark brown	80-90C[(8)]	10 years	B,D	640 m
Costa Rica	G	-	A9918	**clear**	-	10 years	B,C	-
Mohavi Desert	E	a	A9918	**clear**	-	10 years	B	-
"Around the World"	E	a	A9918	**clear**	-	10 years	B	-
Cape Canaveral, FL	A	-	A9918	discolored	-	10 years	A	-
SWRES Las Cruces, NM	D	c	A9918	light amber	75C[(6)]	10 years	B	1198 m

66 Estimated, no "hard" data available, (summer) measurements taken mostly from back-side of module

67 A- Glass/EVA/Cell/EVA/Foil, B- Glass/EVA/Cell/EVA/Film laminate, C- Tefzel/EVA/Cell/EVA/Film laminate, D- Bifacial

68 Average ambient temperature plus 30° C

69 Browning varied from one cell to another within the same module

70 High and low mounted racks

71 Manufacturer's data

72 Estimated based on high wind velocity (ambient temperature plus 20° C)

73 Modules operated at approximately 2 suns (mirror enhanced)

1.5.4: Overview of Results

a. Module manufacturers depend on testing facilities for information that is pertinent to EVA-based encapsulant discoloration. Typically, module testing has not focused on discoloration, and consequently there is limited documentation on the incidence of browning. Most manufacturers had never heard of EVA-based encapsulant browning until the test site sent them discolored modules.

b. In most cases, the exact time for encapsulant discoloration development is not known. Generally, discoloration was not documented until its advanced stages.

c. Survey contacts generally did not have exact data with respect to module operating temperatures and insolation. Generally, maximum module operation temperatures were approximated as 30° C above ambient temperature.

d. Data collected from "project"-type modules generally was pertinent only to determining the overall module efficiency. Module operation temperature, circuitry flaws, module replacement, module rewiring, and array downtime were rarely documented.

e. There is no quantitative information on discoloration. A typical browning analysis is based on visual observation without color standards or quantitative measurements.

f. There had been no reported cases of EVA-based encapsulant browning from Eastern and Central United States or Western Europe, until about a year after the survey was completed. At that time, an EVA-based encapsulant was said to have discolored after 12 years exposure in a module deployed in Maryland.

1.5.5: Correlations Between EVA Discoloration and Various Material, Fabrication, Placement, and Exposure Parameters

EVA Supplier: EVA-based encapsulants covered during this survey were manufactured by Miles, Inc. Berlin, CT (formerly Mobay Konesco and Rowland), Richmond Technology, Inc. Redlands CA, and Springborn Laboratories, Inc., Enfield, CT. Discoloration was not limited to the encapsulant sheet stock of any one supplier.

It is possible that the formulation and process used to produce the EVA-based sheet stock had an effect on discoloration of the resulting fielded modules. It was impossible, however, to determine the effect of each manufacturer on discoloration, since none of the module makers used EVA-based encapsulant from more than one supplier.

There appeared to be distinct differences in discoloration rates between modules of each photovoltaic manufacturer. It is possible that the EVA-based sheet stock supplier was a factor due to differences in formulation and processing parameters.

Formulation:

Virtually all fielded EVA-based encapsulants reported during this survey were 2,5-dimethyl-2,5-(t-butylperoxy)hexane cured formulations. There were two basic formulation types represented in fielded modules; self-priming, and unprimed. All three sheet makers supplied self-priming sheet to the module manufacturing industry. Only two processors, Miles and Springborn, supplied unprimed sheet stock.

EVA-based sheet from two manufacturers appeared to be identical in composition. The third manufacturer, however, uses a different ratio of ingredients than the other manufacturers.

It is possible that formulation/composition had an effect on rate and degree of discoloration of EVA-based encapsulant materials. It should be noted, however, that there are examples of discolored modules containing each of the EVA-based compositions previously described.

Processing:

The processing parameters of each EVA sheet manufacturer were not investigated as part of the survey. Likely each compounder processed the raw materials differently.

EVA-based sheet from each of the manufacturers was found to have discolored after field exposure within a module for 4 to 10 years. It can therefore be concluded that discoloration of EVA-based encapsulant is not caused by any one formulation or film processing procedure. It is likely that processing procedure for EVA-based sheet-stock has an effect on the rate of discoloration in fielded photovoltaic modules since the EVA-based encapsulant sheet-stock contains reactive ingredients.

A correlation between processing parameters and discoloration of EVA-based encapsulants was impossible to make since each photovoltaic manufacturer generally uses EVA-based encapsulants from only one supplier. Performance of different EVA-based encapsulants could not be directly compared since there were other variables such as cell design, module manufacturing, and module operation, to consider when evaluating the encapsulants for discoloration.

Module Manufacturer: There were some definite correlations found between rate of discoloration of EVA-based encapsulant materials and module manufacturer. The Sacramento Municipal Utility District (SMUD), Pacific Gas and Electric (PG&E), and Southwest Regional Experimental Station (SWRES) facilities had representative modules from several manufacturers.

The reasons for differences in module discoloration rate from one manufacturer to another were difficult to ascertain based on the facilities' field reports. Testing sites at SMUD and PG&E provided information from multiple manufacturers. Modules at these testing facilities were fielded under identical conditions with respect to ambient environment, power load, and mount design. This would suggest that manufacturer dependent variables including raw materials, module fabrication processes, module design, and module operation have a significant effect on the rate of discoloration of the photovoltaic modules.

A third test site, SWRES, provided test reports for two different manufacturers. Operating conditions were similar for all modules at this testing facility with exception of mounting design, and manufacturer-dependent variables. Modules having the least discoloration had been mounted on elevated racks which enabled them to operate at cooler temperatures than more discolored modules that were mounted as part of an integral roof rack. Despite differences in mounting, however, relative rates of discoloration at SWRES correlated with reports from the SMUD and PG&E facilities.

Module Construction: There were four basic module construction types reported during our survey: Glass/EVA/Cell/EVA/Foil, Glass/EVA/Cell/EVA/film laminate, Tefzel/EVA/Cell/EVA/film laminate, and bifacial (i.e., cells and glass on both sides of module). Each manufacturer had its own proprietary silicon cell, circuitry, and engineering parameters.

The majority of modules that were reported discolored were glass/EVA/Cell/EVA/film laminates since this was the most common construction. It was beyond the scope of the investigation to make correlations between rate of discoloration and module construction since there is little long term field data for the other three, less popular, construction designs.

There have been general observations by the photovoltaic industry that suggest modules discolor more quickly if the module has poor vapor permeability. Theoretically, the Tefzel construction should have better permeability

than the glass/film laminate, and the glass/film laminate should have better permeability than the glass/foil laminate.

The permeability versus rate of discoloration hypothesis appears to have been supported by data collected during the survey. There were several reports of accelerated discoloration over areas in modules where non-permeable junction boxes or aluminum labels were adhered to the back-side.

Geographic Location and Climate: There appeared to be a strong relationship between geographic location and incidence of EVA-based encapsulant discoloration. There had been no reported cases of encapsulant discoloration from Eastern and Central United States or Western Europe at the time of this survey, while browning was reported in Southern and Western United States. A year after the survey was completed, there was one case of browning reported in Maryland of a module that had been in service for 12 years.

Annual average solar irradiance varies from region to region throughout the country. (Figure 4 - Average Daily Direct Normal Solar Radiation (MJ/m^2), page 24) Reports of browning in the southern and western regions of the country are not surprising when considering the solar insolation distribution. Based on published information[74], southern and western regions of the United States have greater solar irradiance than eastern or central regions. Arizona and New Mexico have approximately 26 MJ/m^2, California has approximately 20-24 MJ/m^2, Colorado has approximately 20 MJ/m^2 average irradiance, Texas has approximately 16-24 MJ/m^2, Florida, Illinois, and Minnesota have approximately 14 MJ/m^2 and the Northeast averages 10-12 MJ/m^2. These differences in irradiation from north to south, and east to west likely result from differences in latitude, elevation, and composition of the atmosphere/troposphere.

Photovoltaic modules fielded in the northeast region of the United States, had approximately a ten year history without discoloration when this survey was done, and now have about 14 years in service. Some modules fielded in California have discolored in as few as 4 years. Differences in performance of the EVA-based encapsulants between the Northeast and other parts of the country appear to correlate with direct normal solar radiation data. Overall, it was impossible to quantify the effect of normal solar radiation on discoloration rate of the EVA-based encapsulants. The manufacturers generally reported when encapsulant discoloration was first realized, rather than at its onset.

One major deficiency in available solar radiation data was absence of solar spectral emission measurements at each test location. Direct normal solar radiation is a measure of total solar radiation, but it does not indicate the energy irradiance for each spectral wavelength.

The ratio of short-wavelength ultraviolet to total radiation potentially is believed to be the same throughout the United States on a given day.[75] Regions of the country that have higher solar insolation will, therefore, have proportionally greater amounts of UV. The proportion of short to long wavelength ultraviolet changes with season, local conditions and time of day. No data was reported on the exact composition of UV energy at each module site, however.

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[74] Insolation Data Manual and Direct Normal Solar Radiation Data Manual, SERI/TP-220-3880 , July 1990.

[75] R.W. Singleton and P.A.C. Cook, Textile Res. J. 39, 43-49 (1969)

AVERAGE DAILY DIRECT NORMAL SOLAR RADIATION (MJ/m2)

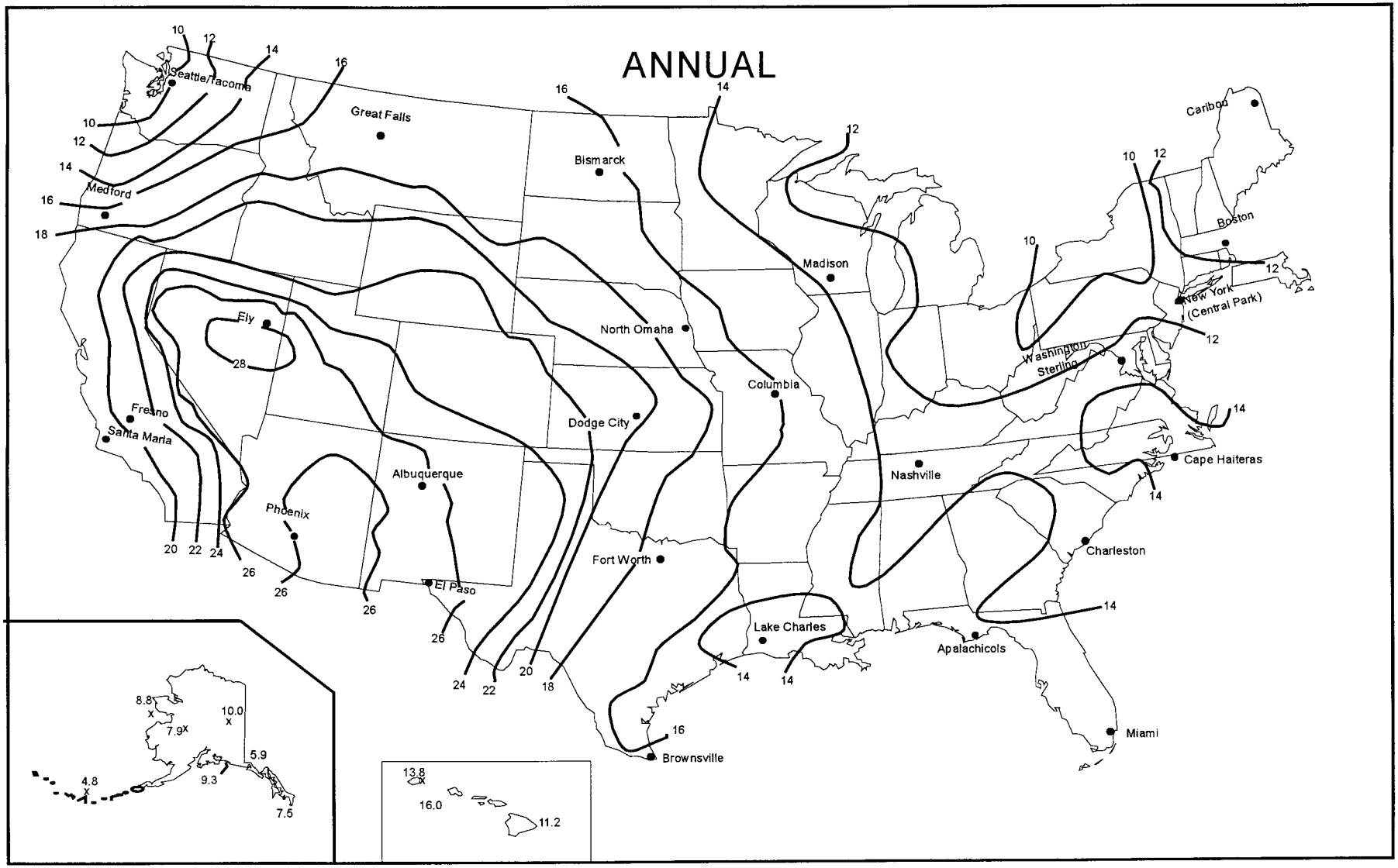

Figure 4 - Average Daily Direct Normal solar Radiation (Mj/m²)

Solar insolation varies with latitude since sunlight's angle of incidence with the earth changes with distance from the equator. Terrestrial solar irradiance is strongest at the equator where sunlight has the most direct path to the earth's surface and, therefore, experiences less air mass to filter out its energy. At latitudes north and south of the equator, sunlight contacts the earth's surface at a lower angle of incidence and must penetrate through a larger volume of atmosphere in order to reach the earth's surface.

Composition of the atmosphere is very important to spectral distribution of solar radiation that reaches the earth's surface. If one assumes the stratosphere is fairly uniform above the entire United States, it would appear that variations in the troposphere might affect the overall solar radiation that reaches the earth at similar latitudes. Areas of the country (West, Southwest) that are very dry with little precipitation, would then tend to get more solar irradiance than areas that are humid with high amounts of precipitation (East, Southeast).

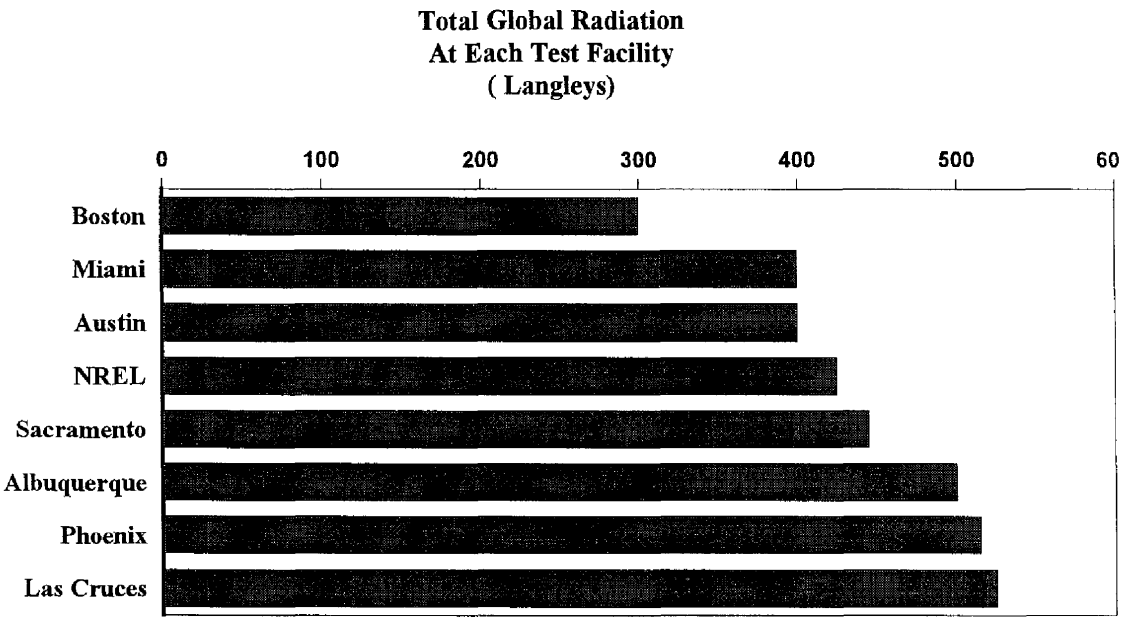

Figure 5 - Total Global Radiation

Based on total global radiation measurements at each testing location (Figure 5 - Total Global Radiation at Each Test Facility), Southwest Regional Experimental Station (SWRES) at Las Cruces NM should have the most severe discoloration, followed by Phoenix, AZ; Albuquerque, NM; Sacramento, CA; NREL; Austin, TX; Miami, FL; and then Boston, MA. In actuality, however, module manufacturers reported EVA-based encapsulant discoloration did not directly correlate with total global radiation reported at each location. For example, there are reports of discolored EVA-based encapsulant at Miami and Austin after seven years, while at NREL, where there is a higher amount of solar insolation, there are separate reports of no discoloration and of slight discoloration after 10 years. Phoenix, AZ was reported to have moderately discolored EVA-based encapsulant while Las Cruces, NM, with the same approximate total global radiation as Phoenix, reported much less discoloration.

While it does appear that total solar insolation correlates with discoloration rate, it is not solely responsible for the rate of EVA-based encapsulant discoloration.

Mounting Variables: Photovoltaics that were fielded at the same test location were not always fielded under identical conditions. Depending on the facility, discoloration from competing manufacturers' modules could not be directly compared due to variables in mounting.

Module Mount Angle

Depending on mount angle, it is possible for modules to receive different levels of solar radiation. An angle that is perpendicular or normal to the sun's radiation will have the maximum possible irradiance for that location. It has been reported that a mount angle of 10 degrees less than the latitude will result in the maximum ultraviolet irradiance since this will ensure a nearly perpendicular presentation to the sun's radiation during the summer months when the ultraviolet content is the highest.[76]

If ultraviolet exposure is indeed a contributor to EVA-based encapsulant discoloration, the angle at which the module is mounted could have an accelerating effect. Manufacturers and test facilities failed to provide sufficient data on mounting angle to draw any conclusions, however.

Tracking Systems

Single axis and double axis tracking systems are often utilized to maximize the modules' irradiance exposure by maintaining an optimal angle of incidence with the sun as it moves across the horizon. Single axis tracking systems, used by two test sites reporting data, theoretically should increase total irradiance exposure of the modules by one third when compared with a fixed mounting angle[77]. Therefore, it is assumed that modules mounted on these systems are exposed to one third more ultraviolet light than modules mounted on stationary mounting systems and that the rate of encapsulant discoloration should also increase by one third.

The SMUD and Austin modules, mounted on single axis tracking systems, appeared to have more pronounced browning than total average global irradiance data would indicate. When the tracking system was considered (Figure 6 - Tracker Enhanced Global Radiation), modules at SMUD should have had by far the greatest discoloration and modules at Austin should have been slightly more discolored than modules at Phoenix. The rate of discoloration of modules mounted on tracking systems does not appear to correlate proportionally with the one third increase in apparent solar irradiance, however.

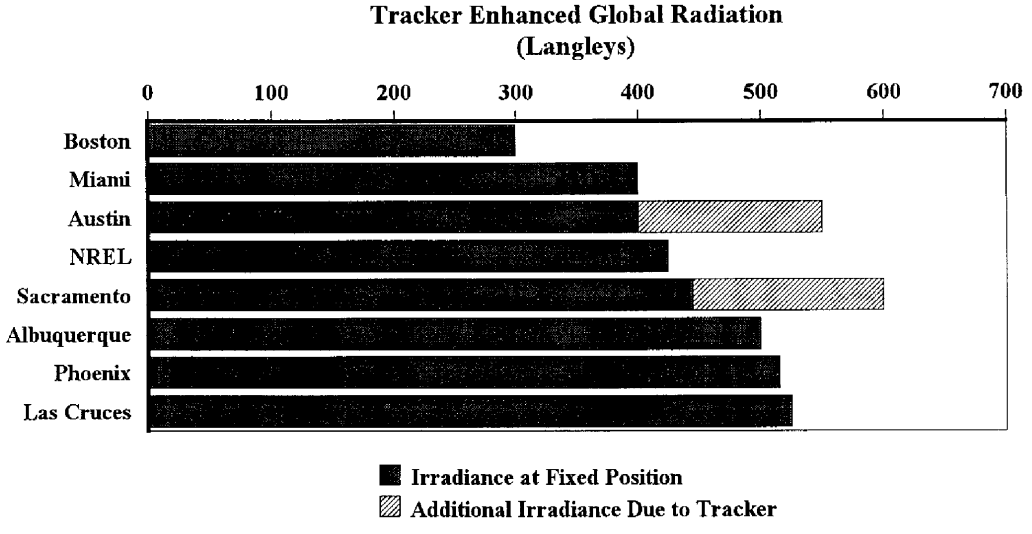

Figure 6 - Tracker Enhanced Global Radiation

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76 G.C. Newland, R.M. Schulken, Jr. and J.W. Tamblyn, *Mater. Res. Stand.* 3, 487-488 (1963)

77 J.E. Clarke, Encyclopedia of Polymer Science and Engineering, Volume 17 p. 796-824, John Wiley and Sons, inc. 1989

Module Mounting Systems

A second mounting variable that was considered during this survey was module mounting system. Generally, modules were fielded using one of five basic mount designs; pole, rack, integral roof mount, standoff roof mount and direct roof mount. Modules fielded on integral and direct roof mounted systems tended to operate at higher temperatures than those on free standing racks or poles. The temperature differential between free standing and roof-mounted systems was most likely due to lack of air circulation around the integral roof mounted racks and to the fact that free standing racks were exposed to the cooling effects of the wind.

It was not possible to isolate the effects of mounting design on discoloration rate of the modules since there were no locations where similar modules were tested on different types of mounting structures. Similarly, each testing facility had different insolation and varying weather conditions which prevented a direct comparison of mounting design with rate of discoloration. One testing site had modules on both rack and integral roof mounted systems. The module operation from each type of rack was not quantified, however.

One example of the effect of cooling potential on discoloration rate of the EVA-based encapsulant might be at the CALTRANS facility at the top of Donner Pass, Caples Lake, CA in the Sierra Nevadas. This rack-mounted array is elevated high off the ground so that winter snow will not cover the modules, and is exposed to maximum wind speeds of 160 KM/h. At the time the survey was done, this system has been in operation for seven years without discoloring. Lack of discoloration at CALTRANS facility might be puzzling if comparing geographic location and solar insolation data. It is has been demonstrated in the laboratory, however, that module operation temperature can accelerate EVA-based encapsulant discoloration[78]. If the potential difference in operating temperatures is considered, it is not surprising that the CALTRANS modules have not discolored.

Regarding discoloration of EVA-based encapsulant materials, representative modules of all mount designs and mount-angles have discolored. It was beyond the scope of the survey to make inferences between mounting design and speed or intensity of discoloration since there were no examples of similar modules mounted at the same testing facilities but at different angles of incidence or with different mount types.

Some module manufacturers considered module installation in the field proprietary in terms of mount angle and tracker systems. Others suggested that modules fielded with 2 axis tracking systems were quicker to discolor than those fielded with fixed tilt systems. This observation on the rate of discoloration of modules on 2 axis tracking systems was unsupported by data that was collected during the survey and also by the literature.[79] (see "Tracking Systems" of this report).

Module Operation Temperature: The module operation temperatures reported for fielded photovoltaics appeared full of contradictions. Module manufacturers generally provided approximate temperature rather than actual data. Exact temperature data was generally not available since very few testing facilities monitored module operation temperatures over a period of time.

For lack of better data, most manufacturers supplied a 30° C correction factor for determining module temperature based on ambient temperature. There were poorly documented exceptions to the ambient plus 30° C temperature based on prevailing winds and module mount design, however.

The 30° C correction factor appears to be supported by data from research conducted under EPRI contract GS-6696[80] at arrays located at Sacramento Municipal Utility District (SMUD), and the City of Austin, Texas. Computer-acquired data detailed in the EPRI report indicates that the maximum temperature experienced by

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78 P.B. Willis, Investigation of Test Methods, Material Properties, and Processes for Solar Cell Encapsulants, 9th Ann. Rep. JPL Contract 954527, 1985 (Jet Propulsion Laboratory, Pasadena, CA).

79 C.R. Caryl in W.E. Brown, ed., Testing of Polymers, Vol. 4, Wiley- Intersciences, New York, 1969, pp. 379-397

80 "Photovoltaic System Performance Assessment for 1988", Prepared by Southwest Technology Development Institute, Las Cruces, New Mexico. Final Report; project 1607-6.

modules during operation is 65-70° C. Generally, this appears to be approximately 30° C above the reported ambient temperature. If the correction factor were applied to ambient temperature data that was reported by one module manufacturer, modules operating at SMUD would have an approximate maximum operating temperature of 77° C. This was 7° C higher than data that was continuously collected at SMUD. It was not clear whether this information was contradictory to the EPRI study since the study did not indicate whether data was based on an average of temperatures collected from modules of all three manufacturers, or whether it reflected only an example of one module/one manufacturer in the array. It is likely that the module operation temperatures vary depending on individual manufacturer and module design.

Due to the approximate nature of module operation temperature data provided by module manufacturers, National Weather Service average maximum temperature data[81] was later used to more accurately correlate module operation temperatures with encapsulant discoloration. Based on National Weather Service Station maximum average daily temperature data (Figure 7 - Maximum Daily Ambient Temperature at Each Photovoltaic Test Facility), modules in Phoenix, AZ potentially operated at annual maximum temperatures greater than at other test sites.

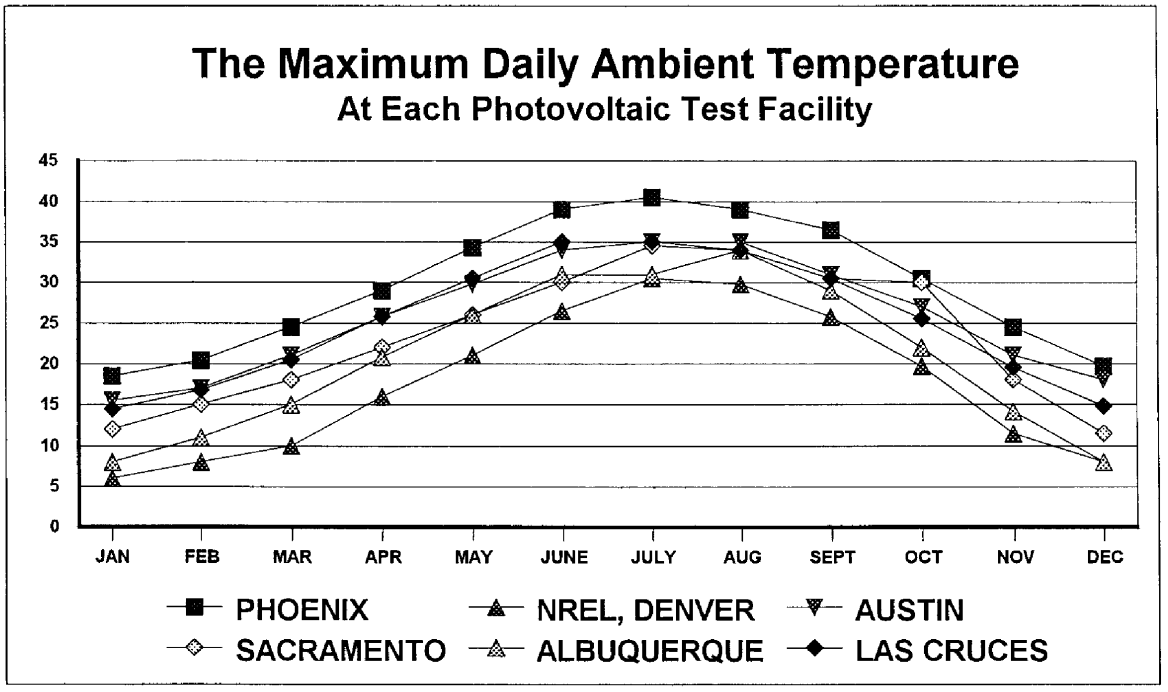

Figure 7 - The Maximum Daily Ambient Temperatures

Ambient temperature profiles for test sites located in Sacramento, CA; Albuquerque, NM; Austin, TX; and Las Cruces, NM[82] were similar. Average ambient temperature at NREL was much cooler than at other Western test sites with the average Denver, CO temperature approximately 10° C cooler than Phoenix, AZ.

When considering the ambient temperature data alone, one might predict that the John Long array in Phoenix, having a 41° C annual maximum ambient temperature, would have the most intense discoloration of all the fielded modules. The modules located at Austin, Sacramento, Albuquerque, and Las Cruces would be less discolored than modules in Phoenix, while modules located at NREL would have the least discoloration of those from any testing facility.

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81 Insolation Data Manual and Direct Normal Solar Radiation Data Manual, SERI/TP-220-3880, July 1990

82 Based on National Weather Service Data for EL Paso,TX

Degree of discoloration of EVA-based encapsulant appears to loosely correlate with ambient temperature information from the National Weather Service. Modules at NREL had a ten year history without browning at the time of this survey. Austin, Sacramento, and Albuquerque had slight browning, while Phoenix was reported to have moderate browning (Figure 8 - Comparison of Operation Temperature with Degree of Browning).

Location	Max. Daily T (°C) (July)	Approx. Module T(°C)	Degree of Browning
Phoenix	41	71	moderate
Austin	35	65	moderate/slight
Las Cruces	35	65	slight
Sacramento	34	64	slight
Albuquerque	33	63	slight
Denver	31	61	no browning
Boston	27	57	no browning

Figure 8 - Comparison of Operation Temperature with Degree of Browning

Other arrays that appear to operate under cooler average maximum ambient temperatures are the CALTRANS array on the top of Donner Pass (32C ambient, maximum daily average July) and the Gardner array in Boston MA (27C ambient, maximum daily average July). At the time this survey was completed, CALTRANS had a seven year history without discoloration while Boston had a ten year history.

Photothermal Effects: Literature in the field of EVA-based encapsulant materials reports a combined effect of temperature and light with respect to discoloration.[83,84,85,86,87] Information collected during the survey of fielded photovoltaic modules illustrates this combined effect (Figure 9 - The Effects of Radiation and Module Temperature on EVA).

Location	Ave. Annual Radiation kJ/m2	Approx. Av. Annual Module T (°C)	Degree of Browning
Phoenix	21216	60	moderate
Austin	16755	56	slight
Las Cruces	21559	55	slight
Sacramento	18645	53	slight
Albuquerque	20740	51	slight
Boston	12537	45	no browning
Denver	17800	38	no browning

Figure 9 - The Effects of Radiation and Module Temperature on EVA

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83 "EVA Degradation Mechanisms Simulating Those in PV Modules", F.J Pern and A.W. Czanderna; Report from DOE contract DE-AC02-83CH10093

84 "Solarex Experience With Ethylene Vinyl Acetate", J. H. Wohlgemuth and R.C. Petersen, Solar Cells Their Science, Technology, Applications and Economics: Elsevier Sequioa; 1991; 30: 563-571

85 "Encapsulant Degradation in Photovoltaic Modules", K.J. Lewis and C.A. Megerle, Journal Polymer Solar Energy Util.; 1983; 220: 387=406; CODEN: ACSMC8; ISSN: 0097-6156.

86 "Investigation of Test Methods, Materials, and Processes for Solar Cell Encapsulants", 7th Ann. Rep., JPL Contract 954527, 1983 (Jet Propulsion Laboratory, Pasadena, CA.)

87 "Photothermal Degradation of Stabilized EVA", Liang et. al. (JPL), Polym. Sci. & Tech. 20 (1982) 267-278

Phoenix, which has both the highest average annual radiation and highest average annual module temperature of surveyed test sites, appears to have the most severe encapsulant discoloration. Boston, on the other hand, has the coolest average module temperature and the lowest average annual radiation, with no EVA-based encapsulant discoloration.

While insolation or temperature data alone can be used to explain discoloration patterns at Phoenix and Boston, this analysis becomes oversimplified when referring to the comparative discoloration of modules at Austin, Las Cruces, Sacramento, Albuquerque, and Denver. When comparing average annual insolation at the Austin and Denver test facilities, one might expect modules at Denver to have more discoloration than modules at Austin. If, instead, the combined module operation temperature and annual insolation data are considered as factors, one would correctly predict that modules at Austin would be more discolored than those at Denver.

Similarly, modules at Phoenix and Las Cruces did not have the same degree of discoloration despite similar amounts of annual radiation. If the average annual temperature difference of 5° C is considered, however, one would correctly predict that modules from Phoenix would be more discolored than those in Las Cruces.

Reports of discolored modules were not quantitative enough to make further observations relating discoloration of modules at Las Cruces, Austin, Sacramento, and Albuquerque. Based on insolation and ambient temperature data obtained from the National Weather Service, however, one might predict that modules at Las Cruces would be more discolored than modules at Austin, Albuquerque, and Sacramento.

1.5.6 Survey Conclusions

a. The incidence of EVA-based encapsulant discoloration is not limited to the modules of any one particular manufacturer.

b. The incidence of EVA-based encapsulant discoloration is not limited to the encapsulant sheet of any one particular supplier.

c. The rate of browning appears to be module manufacturer dependent. There is one module manufacturer who's modules consistently discolor less than any other manufactured modules that have been tested in the field in excess of 4 years.

d. Possible variables affecting the <u>differences</u> in discoloration from manufacturer-to-manufacturer include: EVA-based encapsulant suppliers, encapsulant formulations, processing variables, cell/module design, and operation and/or operation temperature.

e. The incidence of EVA-based encapsulant discoloration appears to be primarily in the West and Southwest where there is comparatively high solar insolation and higher operating temperatures.

f. This discoloration appears to be more intense at test facilities that have a combination of high module operation temperature and high solar insolation.

2.0 FURTHER PROBLEM DEFINITION - LABORATORY AGING STUDIES

2.1 Purpose of this Task

Task 2 of this PVMaT project involved laboratory problem definition work with an emphasis on controlled accelerated U.V. aging studies (AAS) to evaluate the influence of various compositional, processing, and operating parameters on EVA-based encapsulant discoloration. In support of these AAS of coupon-size encapsulant laminates, an Atlas Xenon Arc Ci35A Weather-O-Meter was utilized and calibrated for temperature and irradiance (See Annual report under this subcontract, for the period December 30, 1992 to March 31, 1994).

2.2 Sample Preparation and Testing Methods

2.2.1: Sample Laminates - For these comparative AAS, coupon-size laminates, measuring 2.7 x 2.75 inches and preferably less than 0.255 inches thick, were used. These were prepared by vacuum lamination using commercial time/temperature/vacuum schedules recommended for encapsulation when using either EVA-based formulation, A9918 or 15295, except when the cure schedule was purposely varied in order to assess its effect. A laboratory-scale vacuum laminator and pump were used for this work. A data logger and multiple thermocouples were used to verify temperature profiles of samples cured in the laminator. For most of this work, glass/glass laminates were used to facilitate visual, colorimetric, and spectrographic measurements. However, some laminates contained cells in order to investigate such effects as cell/encapsulant and metallization/encapsulant interfacial chemical changes.

2.2.2: Types of Cover Materials - The superstrate used was low iron glass so as to allow the maximum amount of UV-B light through (i.e., 285 to 350 nm), that wavelength region suspected as being responsible for EVA-based encapsulant discoloration/degradation. Also, low iron glass is the superstrate most commonly used in those fielded modules which have shown a discoloration problem. TPE refers to standard Tedlar/polyester/EVA laminate backing material, where the EVA layer is a non-conformal 4% vinyl acetate content grade (i.e., this EVA is a tie layer rather than an encapsulant).

Low iron glasses used in this task included Solite (AFG - samples from the mid 1980s), Starphire (PPG), Solatex II (AFG - containing cerium oxide, estimated to be at less than 4% by weight), and Solarphire (formerly Airphire: PPG - also containing cerium oxide). Solarphire (Airphire) and Solatex II benefit this application by removing most UV-B radiation between 280 and 330 nm, a region known to be detrimental to polymer stability (see Annual report under this subcontract, for period from December 30, 1992 to March 31, 1994 for further details on these glass superstrates).

2.2.3: Sample Exposure Conditions - Coupon laminates were exposed to 0.55 watts/square meter/nm (taken @ 340 nm) and 100° C in a Ci35A Atlas Xenon-Arc Weather-O-Meter using quartz/borosilicate glass filters. The nominal lower end U.V. cut-off was 285 nm. Samples were exposed for a minimum of 17 weeks or until significant degradation/discoloration of the encapsulant had occurred. In all cases, samples were exposed in duplicate.

Calibration work on the Ci35A revealed that slight temperature and irradiance variations exist between the top, middle, and bottom racks. Some samples were placed so as to assess the effect of this variation. However, since the purpose of the testing was to develop comparative data, most samples were rotated between racks, from top to bottom on a weekly basis, to normalize any minor T/I differences.

Again, it should be emphasized that the Weather-O-Meter was being used <u>only as a screening tool</u> - that is, a laboratory technique for conducting preliminary evaluation of various module encapsulation materials/constructions in order to assess their relative U.V. aging resistance and to obtain a relative ranking of those materials/constructions. There was no attempt to develop firm correlations between accelerated aging results and field information or to develop definitive acceleration factors, both of which are beyond the scope of this investigation.

2.3 Sample Evaluation

Coupons were monitored for color/chemical changes during exposure. Non-destructive tests on the samples included visual fluorescence at 360 nm under a hand held "mineral light" (qualitative test for development of chemical change in the encapsulant), Yellowness Index per ASTM D-1925, and percent light transmission (%T) between 250 and 900 nm by U.V.-VIS spectrophotometer.

Some destructive testing for analysis of additive concentrations and vinyl acetate content was also done. At the conclusion of the accelerated UV exposure period, selected samples were forwarded to NREL for fluorescence spectroscopy and to UCONN/IMS (the Institute of Materials Science at the University of Connecticut) for Task 3 analysis (see section 3.0 of this report for details).

2.4 Aging Results

Quantitative yellowing results can be found in Table 3. Based on these results, contributions of each formulation ingredient to the browning process appear to be as follows:

2.4.1: EVA Resin (Elvax 150 now Elvax 3185) - EVA, as received from the supplier without additional additives of any kind, showed little or no color development after 17 weeks exposure in the Ci35A (see samples 29164-3c through -1b in third grouping, Table 3), with either Starphire or older Solite glass superstrate, i.e., 0.7 to 1.4 color index and no visual yellowing. Neither of these glass superstrates contain cerium dioxide.

By contrast, control samples containing standard A9918P encapsulant showed significant color change over the same period (samples 29168-1a and -2b in fourth grouping Table 3 and 29201-13a and -14b at the bottom of Table 3, continued -3), again with either older Solite or Starphire glass, i.e., 39.1 to 49.6 Yellowness Index, and visually a medium brown color. After 22 weeks aging, these samples developed a yellowness Index of 53.6 to 64, and the Solite covered sample had a Yellowness Index of 82.8 after 36 weeks in the Ci35A (samples 29168-1a and 29201-14b, Table 3, continued - 5).

These results suggest that color development under these moderate conditions of temperature and UV is related to an interaction of the additives. Analytical results seem to verify this (see section 3.0 of this report for details). Whether the additives, after interacting, involve the EVA polymer in some way is not known at this point. What is known, however, is that EVA resin (Elvax 3185) with no additives develops almost no measurable yellow (i.e., 0.7 to 1.4 Yellowness Index) and no visible color.

2.4.2: Peroxide Crosslinker (Lupersol 101) - Surprisingly, samples using A9918P EVA, but without peroxide crosslinker [Lupersol 101; 2,5-dimethyl-2,5-di (t-butylperoxy) hexane] developed comparatively little color after 10 weeks exposure (Yellowness Index of 5.4 to 7.1 versus 18.8 to 19.6 for fully formulated A9918P, Table 3, third grouping). This data suggested that Lupersol 101 peroxide is playing a significant role in discoloration. However, Yellowness Index for these samples (5.4 to 7.1) points out that one or more of the other additives is also contributing to discoloration.

Investigating further, a series was exposed which used Elvax 3185 with only one additive in each laminate (Table 3, continued - 3, series 29203). The sample with only Lupersol 101 developed essentially no color after 17 weeks in the Ci35A (sample 29203-1a), lending additional support for an interaction of Lupersol 101 with one or more of the other additives as a major cause of discoloration.

As a comparison, a set of samples was prepared and exposed using encapsulant 15295P and Solite superstrate. The only difference between 15295P and A9918P is the use of Lupersol TBEC in place of Lupersol 101 to provide a "faster cure." After 17 weeks in the Ci35A, these samples developed a Yellowness Index of only 14.2 to 16.7 (see samples 28937-5 and -6, center of Table 3, continued-4) compared to 39.1 to 40.4 for A9918P. And after 26 weeks, the 15295P-based laminate had a Yellowness Index of 33.7 versus 63.5 for the A9918P-based sample (Table 1, continued-5 and Figure 10).

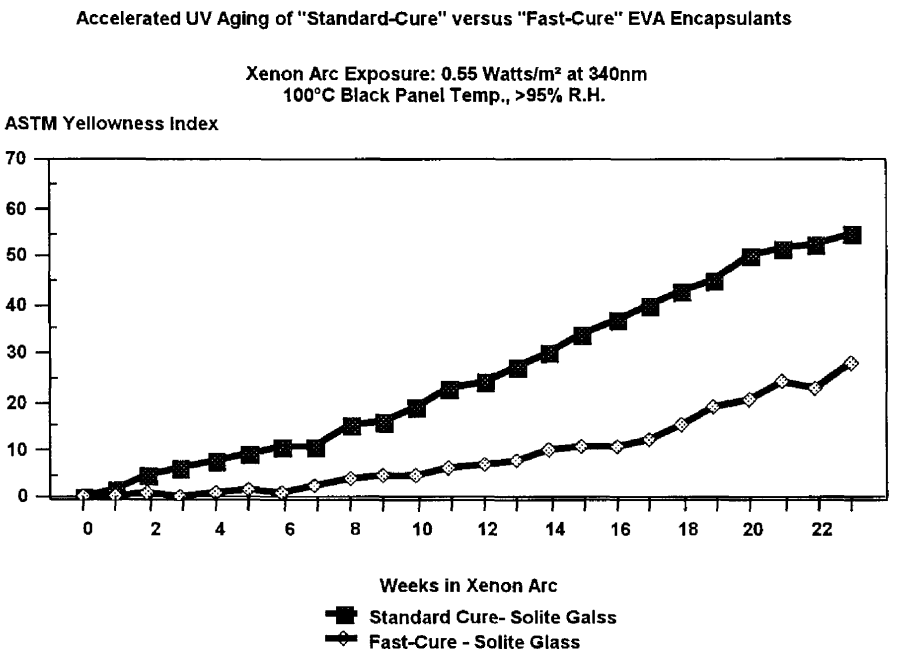

Figure 10 - Accelerated UV Aging of "Standard-Cure" vs. "Fast-Cure" EVA Encapsulants

Again, this comparison implicates peroxide, Lupersol 101 and to a lesser extent Lupersol TBEC, in the color development process.

2.4.3: Phosphite Heat Stabilizer - In the second series of samples in Table 3, continued-2, one additive each was systematically removed from A9918P. After 17 weeks of exposure, samples with no phosphite (Naugard P) additive (29163-2 and -1) showed significantly less yellowing (i.e., 18.7 to 23.6) than the A9918P control (39.1 to 40.4).

As noted above, a series was run using Elvax 3185 with only one additive in each sample (center of Table 3, continued -3). Interestingly, the only samples to develop a significant degree of color were those with Naugard P These laminates exhibited a Yellowness Index of 10.7 to 11.4 after 17 weeks in the Weather-O-Meter.

However, the above experiments caused us to suspect that color formation might also be influenced by an interaction of two or more additives, likely Lupersol 101 and Naugard P, but possibly Lupersol 101 with others. Consequently, we conducted a third series with binary combinations of additives in Elvax 3185 -Lupersol 101 plus one other additive (Table 3, continued -4, top series 29208-1a through -10A).

After 17 weeks exposure in the Ci35A, the glass/EVA/glass laminates with Lupersol 101 and Naugard P showed significant color development (Yellowness Index of 11.4 to 11.5) but no more so than with Naugard P alone (see above). Samples with Lupersol 101 in combination with Tinuvin 770 or Z6030 silane did not develop significant color.

These results seem to discount a Lupersol 101/Naugard P interaction leading to chromophore development.

2.4.4: U.V. Absorber (Cyasorb UV 531) - As indicated above, in the second series of samples listed in Table 3, continued -2, one additive each was systematically removed from A9918P. Removal of UV-531 greatly reduced color development (samples 28938-5 and -6) when compared with the A9918P control.

In addition, in the series which explored binary additive combinations (Table 3, continued - 4, first series, 29208), samples with Lupersol 101 plus UV-531 showed significant color development after 17 weeks exposure in the

Ci35A (Yellowness Index of 22.3). Also, analytical results by UCONN/IMS on Weather-O-Meter aged samples support a Lupersol 101/UV-531 interaction (see Section 3.0 of this report for details).

2.4.5: Glass Superstrates (Solite circa 1980s versus Solite II and Solatex II, Starphire and Solarphire) - After 17 weeks aging, some significant differences in discoloration showed up in samples of A9918P using different types of glass superstrate (Table 3, fourth grouping and bottom of Table 3, continued -3). Solarphire (formerly Airphire) appears most effective at slowing the rate of discoloration (Yellowness Index of 9.3 at 17 weeks), but Solatex II is also very effective (Yellowness Index of 9.8 to 10.3), and differences in results between these two cerium-oxide-containing glasses may be within experimental error (see Figure 11). After 35 weeks aging, the Solarphire (Airphire)-covered laminate had a Yellowness Index of 17.8, while the sample prepared with Solatex II developed a Yellowness Index of 23.8 (Table 3, continued -5).

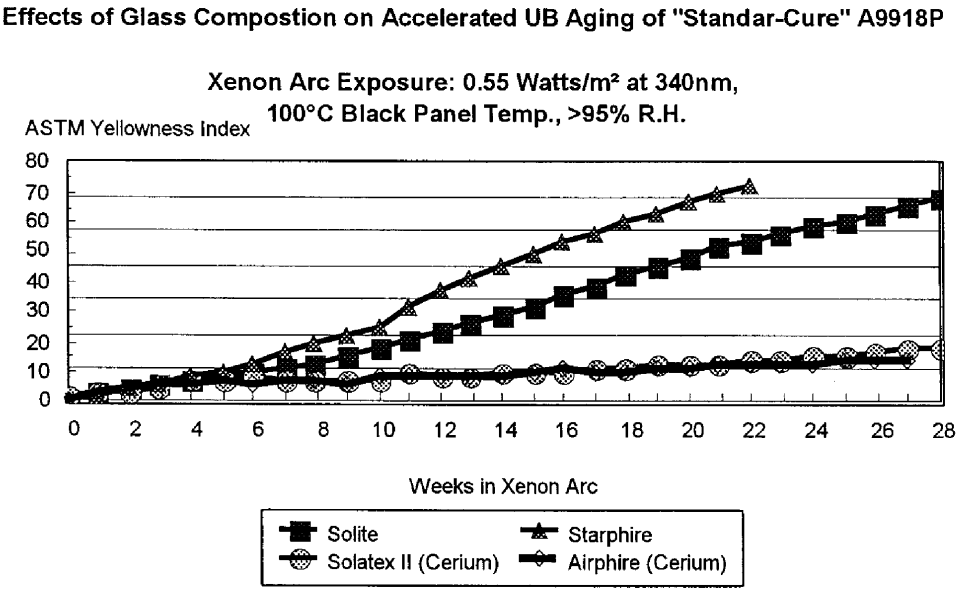

Figure 11 - Effects of Glass Composition on Accelerated UV Aging of "Standard-Cure" A9918P EVA

The control, Solite, allowed a 17 week Yellowness Index of 39.1 to 40.4, while encapsulant discoloration with Starphire was somewhat worse, with a Yellowness Index of 48.7 to 49.6. After 35 weeks in the Ci35A, the Solite-covered sample had a Yellowness Index of 81.9 (Table 3, continued -5, sample 29168-1a), compared with 17.8 to 23.8 for samples prepared with cerium-oxide containing glass, as noted in the preceding paragraph.

It is noteworthy that Starphire transmits more light in the 280 to 320 nm wavelength region than does Solite, and this could account for the difference in discoloration rate (see Figures 8-11 in the Annual Report under this subcontract for the period December 30, 1992 to March 31, 1994).

2.4.6: Breathable Substrates and Superstrates - When an oxygen permeable substrate or superstrate is used in place of one of the layers of glass, comparatively little color development occurs. For example, A9918P-based laminates prepared with Solite glass and no backing had Yellowness Index, after 17 weeks of Weather-O-Meter aging, of only 3.1 to 3.3 and only 4.5 after 26 weeks (Table 1 first grouping, and Table 1, continued -5, first entry). Also, samples prepared with 10 mil Tedlar backing, had no visible discoloration after 17 weeks of aging (Table 3, second grouping).

When Tedlar or Tefzel was used as the superstrate, with low iron glass as the substrate and A9918P as encapsulant, Yellowness Index readings of only 2.0 to 2.9 were recorded after 17 weeks in the Ci35A (Table 3,

continued -3, fourth grouping). And after 32 weeks, the Tefzel-covered sample had a Yellowness Index of only 3.9 (Table 3, continued -5, third grouping).

Analytical work revealed that oxidation is taking place in the encapsulant in such permeable areas, and we speculate that either chromophores are being oxidized as well, or their formation is being inhibited by the presence of oxygen. (See section 3.0 of this report for details)

2.5 Outdoor EMMA Accelerated Weathering Tests

For added confirmation of laboratory accelerated aging data based on Atlas Ci35A Xenon-Arc Weather-O-Meter exposure, selected samples were submitted to DSET Laboratories Inc., Phoenix, Arizona, where they were subjected to EMMA (Equatorial Mount with Mirrors for Acceleration) accelerated outdoor exposure. Samples, prepared in duplicate, included:

Solite (circa 1980s)/A9918P/Starphire (substrate)

Solatex II/A9918P/Starphire

Tefzel/A9918P/Starphire

Solite (circa 1980s)/15295P (with Lupersol TBEC)/Starphire

Solatex II/15295P/Starphire

Solite/A9918P/cells/Tedlar film laminate

These samples were evaluated monthly by DSET Labs for Yellowness Index (see Table 4). Control material A9918P with either Solite or Starphire glass superstrate developed measurable yellowing (i.e., Yellowness Index increase of 13.8 to 15.7) after 36 weeks of exposure, which should be equivalent to approximately 3.5 years of Arizona sunlight (EMMA intensifies the incident light in the UV region of the spectrum by a factor of X5). By 69 weeks of exposure, these samples were a distinct amber color (Yellowness Index increase of 35.6 to 36.0). While the fast cure 15295P yellowed after 69 weeks under non-cerium glass, the Yellowness Index increase was only 7.4, which is consistent with relative results found after Weather-O-Meter exposure.

As in the Weather-O-Meter, use of cerium oxide containing Solatex II glass greatly reduced the yellowing of A9918P and 15295P during EMMA (Yellowness Index increases after 69 weeks of 2.0 and 0.5, respectively). And as found with exposure in the Ci35A, use of a breathable Tefzel superstrate resulted in no measurable yellowing.

2.6 Conclusions from Aging Studies

These Task 2 results suggest that the photochemistry of EVA-based encapsulant A9918P is related to stabilization additives interacting with residual Lupersol 101 peroxide. EVA base resin, Elvax 3185, does not appear to be a significant contributor to color, unless reaction products of stabilizers with Lupersol 101 are in turn involving the polymer in some way. And even if the polymer is involved, subsequent analytical work has not been able to detect any polyenes. Another chemical species appears to be giving rise to the yellowing.

Analytical results corroborate these finding, as discussed in Section 3.0 of this report.

Use of cerium oxide-containing glass greatly reduces the rate of discoloration of A9918P, presumably by filtering out much of the UV-B radiation (i.e., 280 to 340 nm).
Also, use of Lupersol TBEC, as a replacement for Lupersol 101, significantly reduces the rate of encapsulant discoloration.

And, when Lupersol TBEC-based encapsulant is employed with Solarphire (Airphire) or Solatex II cerium-oxide containing superstrate, color development is nearly eliminated. After 29 weeks in the Ci35A Weather-O-Meter, laminates prepared with either Solatex II or Solarphire (Airphire) show no visible discoloration, and a Yellowness Index of only 5.1 to 7.9 (see Table 3, continued -5, center of page).

Table 3

Yellowness Index Measurements (not corrected for yellowness due to 100°C Oven Aging)

For Glass/EVA/Glass Laminates (1)

Samples ROUPED IN PAIR	Construction (2)	0 Weeks	1 week	2 weeks	3 weeks	4 weeks	5 weeks	6 weeks	7 weeks	8 weeks	9 weeks	10 weeks	11 weeks	12 weeks	13 weeks	14 weeks	15 weeks	16 weeks	17 weeks
	"No Backing"																		
29167-4c	A9918P/Starphire/no back	0.8	0.6	0.6	1.0	1.5	1.3	2.8	2.0	2.0	1.8	0.8	-	-	-	-	-	-	-
29167-3a	A9918P/Starphire/no back	0.7	0.6	0.6	1.5	1.7	1.5	2.8	2.0	2.4	2.3	1.3	-	-	-	-	-	-	-
29167-2b	A9918P/Solite/no back	1.2	1.4	1.8	2.5	2.5	2.5	3.8	3.3	3.2	3.2	2.8	3.5	3.7	3.3	3.2	3.1	3.4	3.1
29167-1b	A9918P/Solite/no back	1.4	1.5	1.5	2.0	2.6	3.6	3.8	3.1	3.2	3.1	3.1	3.3	3.7	3.2	3.3	3.3	3.5	3.3
29166-3c	Solatex II (Cerium)/no back	1.4	1.5	1.6	2.2	2.7	3.6	4.5	3.1	4.0	3.7	3.3	4.6	4.5	4.3	4.5	4.3	4.6	4.2
29166-4a	Solatex II (Cerium)/no back	1.6	1.6	1.3	2.3	2.5	2.5	3.6	2.2	3.2	3.0	2.6	3.7	4.1	3.6	3.5	3.3	3.7	4.4
	"Special Backing"																		
28938-1	101/Starphire/10 mil Tedlar Back	0.0*	-0.7*	-0.4*	-1.3*	-0.7*	2.6*	-0.2*	-0.2*	0.1*	0.1*	-0.3*	0.3*	0.2*	0.6*	0.4*	0.5*	0.3*	0.7*
28938-2	101/Starphire/10 mil Tedlar Back	0.0*	-1.0*	-1.0*	-1.6*	-1.0*	1.9*	-0.3*	-0.2*	0.1*	-0.1*	-0.1*	-0.0*	0.2*	0.1*	0.1*	0.2*	0.2*	0.2*
	"Sample edges sealed with epoxy"																		
29164-3c	Elvax 3185 as received/Starphire	0.1	0.1	0.1	0.1	0.9	0.3	1.6	0.9	1.0	0.9	-0.3	-	-	-	-	-	-	-
29164-4a	Elvax 3185 as received/Starphire	0.6	0.3	0.2	0.0	1.0	0.8	1.7	0.8	1.1	0.7	0.3	2.0	1.6	0.9	1.3	1.2	1.3	1.4
29164-2c	Elvax 3185 as received/Solite	0.4	0.7	0.6	0.5	1.6	1.2	2.0	0.9	2.0	1.3	1.1	2.7	2.2	1.7	2.0	2.1	2.0	2.1
29164-1b	Elvax 3185 as received/Solite	0.8	1.0	0.9	0.8	1.6	1.1	2.0	1.1	2.0	1.3	1.2	2.6	2.1	1.7	2.1	2.0	2.2	2.3
29163-3c	No peroxide/Solite	0.5	1.0	1.0	1.3	2.2	1.7	3.4	3.1	4.7	5.3	5.4	-	-	-	-	-	-	-
29163-4a	No peroxide/Solite	0.6	1.2	1.2	1.9	2.5	2.2	4.2	3.9	5.5	6.6	7.1	-	-	-	-	-	-	-
29165-3	A9918P/Solite	1.5	2.8	4.4	5.7	7.3	7.0	11.0	12.3	15.0	18.1	19.6	-	-	-	-	-	-	-
29165-4	A9918P/Solite	0.9	2.9	4.1	5.8	7.1	8.4	10.5	11.8	14.1	17.2	18.8	-	-	-	-	-	-	-
29175-2c	Vacuum cured /Starphire	-0.3	-0.1	1.6	6.0	13.8	19.1	23.6	27.4	29.4	30.2	32.6	34.5	36.3	36.3	37.4	38.2	38.3	40.5
29175-1b	Vacuum cured /Starphire	-0.1	0.1	1.1	4.9	9.9	17.7	21.8	25.2	30.9	33.5	37.9	39.8	41.1	44.4	46.4	47.4	49.1	50.9
29174-4a	15' oven post cure/Starphire	-0.8	1.2	3.4	5.7	6.4	8.7	9.7	11.3	14.6	17.2	21.8	24.9	27.9	31.9	36.1	40.5	43.9	47.6
29174-3c	15' oven post cure/Starphire	-0.7	1.5	3.8	7.0	7.7	10.1	10.3	13.0	16.0	18.7	22.9	26.2	28.9	32.6	36.9	40.9	44.7	48.4
29174-1a	A9918P/Starphire	0.5	1.6	4.5	7.3	7.7	10.0	11.1	14.0	16.9	19.5	-	-	-	-	-	-	-	-
29174-2b	A9918P/Starphire	0.7	1.8	4.9	7.0	7.6	9.8	11.3	14.2	17.3	19.9	-	-	-	-	-	-	-	-
	"A9918P Standard"																		
29166-2c	Solatex II (Cerium)	1.7	2.4	3.2	4.7	5.8	5.7	7.2	6.7	6.7	7.0	6.9	8.5	8.4	8.3	8.8	9.3	9.8	10.3
29166-1b	Solatex II (Cerium)	1.8	2.5	3.5	4.6	6.1	6.5	7.2	6.4	7.0	7.1	6.8	8.4	8.2	8.1	8.7	8.9	9.4	9.8
29176-6c	Window Glass	-1.1	0.0	1.5	3.2	3.2	4.2	4.0	5.0	5.3	5.0	6.9	7.7	7.6	8.6	9.8	10.7	11.6	12.9
29176-5b	Window Glass	-1.1	0.3	1.7	3.4	3.8	3.9	4.1	5.0	5.2	4.9	7.3	7.7	7.4	8.6	9.5	10.5	11.3	12.4
29176-3c	Airphire (Cerium)	1.0	2.6	3.8	4.9	4.5	6.9	5.6	6.2	6.5	5.6	7.4	7.7	7.3	7.5	7.8	8.0	8.2	-
29176-4a	Airphire (Cerium)	0.6	2.8	3.9	5.2	6.1	7.3	6.2	6.6	7.0	6.2	8.2	8.2	7.9	8.3	8.3	8.8	8.9	9.3
29168-1a	Solite	0.7	2.8	4.1	6.2	7.3	8.2	10.2	11.4	13.5	15.8	18.3	21.6	23.6	25.9	29.0	32.3	35.7	39.1
29168-2b	Solite	1.2	2.9	4.3	5.6	7.1	7.6	10.8	12.0	14.2	16.7	19.2	22.6	25.0	27.3	30.3	33.6	37.2	40.4
29154-8a	Starphire	0.4	1.5	3.6	4.2	5.3	7.2	9.5	12.7	14.9	17.5	21.1	24.5	26.7	-	-	-	-	-
29154-7a	Starphire	0.2	1.9	4.4	5.0	6.2	8.2	11.0	13.9	16.4	19.1	23.5	26.6	28.7	-	-	-	-	-
	"Thin EVA layer"																		
29176-2b	EVA 9.5 mils /Starphire	0.4	0.6	2.5	3.2	3.9	8.6	10.7	15.6	19.2	22.3	-	-	-	-	-	-	-	-
29176-1a	EVA 9.5 mils /Starphire	-0.5	0.7	1.7	3.7	4.4	8.9	11.4	13.4	18.7	21.6	-	-	-	-	-	-	-	-
29154-16m	EVA 12 mils/Starphire	-0.1	1.3	0.2	2.9	4.8	7.8	11.2	14.0	18.8	21.6	26.6	30.6	32.9	-	-	-	-	-
29154-15m	EVA 12 mils/Starphire	-0.2	1.3	3.1	3.0	5.0	7.7	11.0	13.4	18.6	21.9	26.2	29.8	32.5	-	-	-	-	-

(1) ASTM D1925-70 Standard Test Method for Yellowness Index of Plastics, Byk Gardner Colorgard System 1000

(2) 150°C laminator for 5.5 minutes; post cured in an oven at 150°C for 1 hr : 18 mil EVA layer

* Yellowness index was normalized to eliminate contribution from haze

09/27/94

Table 3

Yellowness Index Measurements (not corrected for yellowness due to 100°C Oven Aging)

For Glass/EVA/Glass Laminates (1)

Samples ROUPED IN PAIR	Construction (2)	0 Weeks	1 week	2 weeks	3 weeks	4 weeks	5 weeks	6 weeks	7 weeks	8 weeks	9 weeks	10 weeks	11 weeks	12 weeks	13 weeks	14 weeks	15 weeks	16 weeks	17 weeks
	"!8 mil A9918P"																		
29154-8a	Starphire/ "A" rotation	0.4	1.5	3.6	4.2	5.3	7.2	9.5	12.7	14.9	17.5	21.1	24.5	26.7	-	-	-	-	-
29154-7a	Starphire/ "A" rotation	0.2	1.9	4.4	5.0	6.2	8.2	11.0	13.9	16.4	19.1	23.5	26.6	28.7	-	-	-	-	-
29154-9b	Starphire/ "B" rotation	0.1	1.6	3.3	4.3	5.3	7.0	9.4	12.5	14.5	17.5	-	-	-	-	-	-	-	-
29152-1b	Starphire/ "B" rotation	0.4	2.3	4.6	5.0	6.3	7.6	9.8	10.8	13.7	16.3	-	-	-	-	-	-	-	-
29152-2c	Starphire/ "C" rotation	-0.4	1.7	3.7	4.1	5.3	7.5	9.8	12.9	15.6	18.2	-	-	-	-	-	-	-	-
29154-10c	Starphire/ "C" rotation	0.4	2.2	4.2	5.7	6.7	8.7	11.2	14.9	17.1	19.5	-	-	-	-	-	-	-	-
29154-2u	Starphire/ upper rack	0.3	2.2	4.3	5.3	6.4	8.3	11.0	13.6	16.4	19.3	-	-	-	-	-	-	-	-
29154-1u	Starphire/ upper rack	0.2	2.3	4.6	5.7	6.8	8.6	11.1	12.9	16.2	18.9	-	-	-	-	-	-	-	-
29154-3m	Starphire/middle rack	0.1	1.9	4.2	5.2	6.6	8.6	11.4	15.9	17.6	20.8	25.2	28.7	32.4	-	-	-	-	-
29154-4m	Starphire/middle rack	-0.0	2.1	4.3	5.3	6.6	8.4	11.7	15.3	17.8	20.8	24.9	28.4	31.7	-	-	-	-	-
29154-11m	Solite/ middle rack	0.6	2.6	4.4	5.1	6.2	8.1	10.3	12.6	15.0	17.7	21.7	24.4	26.6	-	-	-	-	-
29154-12m	Solite/ middle rack	0.6	2.6	4.8	5.4	6.2	7.5	9.5	11.2	13.9	16.2	18.9	21.6	23.2	-	-	-	-	-
29154-5l	Starphire/lower rack	0.1	1.8	5.7	5.4	6.9	8.7	11.3	13.5	16.8	20.1	-	-	-	-	-	-	-	-
29154-6l	Starphire/lower rack	0.1	2.1	4.7	5.3	6.8	8.4	11.1	14.0	16.3	19.6	-	-	-	-	-	-	-	-
	"Process and Formulation Variations"																		
29161-4a	Milled "A9918P"/Starphire	0.8	1.6	2.4	3.8	5.7	6.3	11.0	13.3	-	-	-	-	-	-	-	-	-	-
29161-3c	Milled "A9918P"/Starphire	0.9	2.1	3.4	4.7	6.2	6.8	10.1	11.5	14.7	17.2	18.7	-	-	-	-	-	-	-
29154-13m	A9918P/Starphire/tin side inward	0.1	2.0	4.4	5.8	6.9	9.2	11.9	15.4	18.4	21.1	25.7	29.8	33.5	37.9	40.7	44.0	47.5	51.3
29154-14m	A9918P/Starphire/tin side inward	0.0	2.2	4.4	5.7	7.0	9.0	12.3	15.0	19.0	21.6	26.1	29.7	33.4	37.7	40.3	43.1	46.8	49.9
29161-1a	Milled "A9918P"/Solite	2.1	3.2	4.6	5.9	7.4	7.9	10.6	11.8	-	-	-	-	-	-	-	-	-	-
29161-2b	Milled "A9918P"/Solite	1.5	3.2	4.3	5.1	6.6	6.9	9.5	10.6	12.2	15.6	16.8	-	-	-	-	-	-	-
29163-2	No phosphite /Solite	1.1	2.5	3.9	4.9	5.5	5.6	6.8	7.0	8.0	8.7	9.3	11.5	12.1	12.8	14.3	15.6	17.1	18.7
29163-1	No phosphite /Solite	2.2	4.5	5.8	6.5	7.2	7.2	8.6	9.2	11.0	11.6	12.6	15.1	15.7	16.6	18.4	19.9	21.7	23.6
29162-4	No silane/Solite	1.5	3.0	4.1	5.3	6.7	7.6	9.4	10.2	-	-	-	-	-	-	-	-	-	-
29162-3	No silane/Solite	1.6	3.2	4.6	6.2	7.8	8.2	10.2	10.5	13.3	15.1	17.0	-	-	-	-	-	-	-
29162-2	No Tmuvin 770/ Solite	1.9	3.7	4.6	6.0	7.4	7.7	9.9	10.1	13.3	14.7	16.8	-	-	-	-	-	-	-
28938-5	No UV531/Starphire	-0.4	1.9	2.4	2.6	4.1	6.6	5.0	5.5	6.0	6.0	5.9	6.5	6.6	7.1	7.0	6.9	6.8	7.2
28938-6	No UV531/Starphire	-0.4	1.8	2.3	2.5	4.0	6.6	4.8	5.3	5.8	6.0	5.9	6.3	6.3	6.9	6.9	6.8	6.8	7.0

(1) ASTM D1925-70 Standard Test Method for Yellowness Index of Plastics, Byk Gardner Colorgard System 1000

(2) 150°C laminator for 5.5 minutes; post cured in an oven at 150°C for 1 hr ; 18 mil EVA layer

* Yellowness index was normalized to eliminate contribution from haze

09/27/94

Table 3

Yellowness Index Measurements (not corrected for yellowness due to 100°C Oven Aging)

For Glass/EVA/Glass Laminates (1)

Samples ROUTED IN PAIR	Construction (2)	0 Weeks	1 week	2 weeks	3 weeks	4 weeks	5 weeks	6 weeks	7 weeks	8 weeks	9 weeks	10 weeks	11 weeks	12 weeks	13 weeks	14 weeks	15 weeks	16 weeks	17 weeks
"A9918P formulated with UV531 Concentration / Starphire"																			
28938-7	UV531	0.3	2.5	3.9	4.4	6.4	10.3	10.3	13.3	16.6	20.2	23.7	28.0	31.7	35.7	38.9	41.9	44.9	48.1
28938-8	UV531	0.2	2.7	4.4	4.2	6.3	10.3	10.2	12.9	16.3	19.4	22.9	26.6	30.6	34.0	37.5	44.2	44.4	47.4
28938-9	Double UV 531	0.6	3.1	5.7	7.0	9.3	12.9	12.9	15.3	18.2	21.4	24.3	28.3	-	-	-	-	-	-
28938-10	Double UV 531	0.6	3.4	5.7	6.7	9.1	13.0	12.9	15.6	18.8	22.0	24.9	29.0	32.2	35.8	38.8	42.1	45.1	48.2
28938-11	Triple UV531	-0.3	2.3	4.6	10.2	15.7	20.5	20.2	22.1	23.9	25.1	25.4	26.8	27.4	28.4	28.6	29.0	29.5	29.7
28938-12	Triple UV531	-0.2	2.4	5.0	11.7	17.6	22.2	22.7	24.7	26.4	27.4	27.9	29.6	30.2	31.1	31.4	32.1	32.6	32.7
"EVA Plus One Ingredient/ Epoxy Sealed / Starphire"																			
29203-1a	Just 101 cured	-0.8	-0.4	0.4	-0.3	0.6	0.4	0.2	1.3	1.4	1.1	1.1	-	1.2	1.0	1.1	0.9	1.2	1.1
29203-2b	Just 101 cured	-0.6	-0.2	0.5	-0.1	0.6	0.6	-0.8	-	-	-	-	-	-	-	-	-	-	-
29203-3a	Just 101 uncured	0.4	0.0	0.8	-0.1	0.8	0.6	0.6	-	-	-	-	-	-	-	-	-	-	-
29203-4c	Just 101 uncured	0.6	0.1	0.6	0.3	0.9	0.8	0.4	-	-	-	-	-	-	-	-	-	-	-
29203-5b	Just 770	-0.2	-0.2	0.2	-0.7	0.1	0.2	-0.8	-	-	-	-	-	-	-	-	-	-	-
29203-6c	Just 770	-0.3	-0.4	0.0	-0.5	0.4	0.0	-0.8	-	-	-	-	-	-	-	-	-	-	-
29203-7a	Just Naugard P	0.8	-0.0	0.9	0.3	1.2	1.7	1.4	3.3	4.4	4.4	5.4	6.2	7.5	8.0	9.0	9.5	11.0	11.4
29203-8b	Just Naugard P	0.9	-0.1	1.0	0.3	1.1	1.6	1.5	3.6	4.6	4.2	5.2	5.9	7.0	7.5	8.5	9.2	10.3	10.7
29203-9c	Just Z6030	0.0	-0.5	-0.0	-0.2	0.5	0.1	-0.8	-	-	-	-	-	-	-	-	-	-	-
29203-10a	Just Z6030	0.0	-0.2	-0.3	-0.2	0.3	0.3	-0.8	-	-	-	-	-	-	-	-	-	-	-
29203-11b	Just UV 531	-0.2	0.3	0.1	-0.0	0.1	0.3	-0.9	-	-	-	-	-	-	-	-	-	-	-
29203-12c	Just UV 531	-0.1	-0.1	0.1	-0.4	0.5	0.3	-0.8	-	-	-	-	-	-	-	-	-	-	-
"Alternative Cover Materials"																			
29202-1c	Tedlar Cover, TUT20BG3	0.0*	-1.1*	-0.5*	-0.7*	-1.3*	-0.3*	-0.8*	0.2*	0.9*	0.5*	0.6*	0.5*	1.5*	1.0*	1.3*	1.3*	1.3*	2.6*
29202-2b	Tedlar Cover, TUT20BG3	0.0*	-1.3*	-0.6*	-1.0*	-0.1*	-0.2*	-0.2*	0.9*	2.0*	0.9*	1.3*	1.4*	1.4*	1.1*	1.9*	2.1*	2.7*	2.9*
29202-3a	Tefzel T²ZM-C cover	1.0	4.2	0.9	0.6	1.6	1.8	1.3	1.8	2.2	1.9	2.1	2.1	2.1	1.7	2.0	1.9	2.4	2.0
29202-4c	Tefzel T²ZM-C cover	1.3	0.8	1.7	1.0	2.3	1.9	1.4	2.3	2.8	2.3	2.5	2.3	2.6	2.2	2.3	2.2	2.5	2.4
"5/5/94 Control"																			
29201-13a	A9918P"/ Starphire Control 5/5/94	0.6	1.5	4.4	5.3	7.1	8.4	11.0	14.9	17.0	20.3	24.4	28.2	32.3	35.7	39.2	42.7	45.3	48.7
29201-14b	A9918P"/ Starphire Control 5/5/94	0.7	1.6	4.3	5.4	7.2	8.7	11.2	14.6	17.5	20.0	24.1	28.1	32.3	36.2	39.8	43.4	46.4	49.6
""LLDPE / Starphire"																			
28938-15	Norchem 831/ No EVA	0.0*	2.2*	2.0*	1.2*	2.5*	4.7*	2.9*	3.0*	3.9*	3.9*	4.1*	5.1*	5.6*	6.4*	7.0*	8.0*	9.0*	10.2*
28938-16	Norchem 831/ No EVA	0.0*	1.8*	2.7*	1.3*	2.5*	4.9*	2.7*	2.9*	3.9*	3.8*	4.0*	5.0*	5.3*	6.1*	6.8*	7.6*	8.4*	9.4*

(1) ASTM D1925-70 Standard Test Method for Yellowness Index of Plastics, Byk Gardner Colorgard System 1000

(2) 150°C laminator for 5.5 minutes; post cured in an oven at 150°C for 1 hr ; 18 mil EVA layer

* Yellowness index was normalized to eliminate contribution from haze

09/27/94

Table 3

Yellowness Index Measurements (not corrected for yellowness due to 100°C Oven Aging)

For Glass/EVA/Glass Laminates (1)

Samples ROUPED IN PAIR	Construction (2)	0 Weeks	1 week	2 weeks	3 weeks	4 weeks	5 weeks	6 weeks	7 weeks	8 weeks	9 weeks	10 weeks	11 weeks	12 weeks	13 weeks	14 weeks	15 weeks	16 weeks	17 weeks
	"Peroxide Plus / starphire"																		
29208-1a	1/3 101	-0.5	-0.9	0.1	-0.1	-1.2	1.4	1.0	0.6	0.7	0.4	0.8	0.4	0.5	0.7	0.9	0.7	1.0	0.7
29208-2c	1/3 101	-0.0	-0.6	0.0	-0.1	-0.7	1.4	0.2	0.5	0.6	0.5	0.8	0.5	0.6	0.7	0.9	0.9	1.0	0.7
29208-3c	101 plus 770	0.5	0.0	0.6	0.5	0.1	2.2	1.7	1.0	1.3	1.1	1.3	1.0	1.0	-	-	-	-	-
29208-4A	101 plus 770	-0.7	0.3	0.8	0.6	0.2	2.2	2.0	1.2	1.3	1.1	1.4	1.0	1.2	1.2	1.3	1.3	1.5	1.0
29208-5B	101 plus UV531	1.7	1.6	3.3	4.1	4.2	6.9	7.4	7.8	8.4	9.6	11.4	11.5	13.5	-	-	-	-	-
29208-6C	101 plus UV531	1.4	1.5	3.5	4.6	4.6	6.8	8.0	7.6	8.9	10.2	11.6	12.7	14.4	15.9	17.7	19.4	21.2	22.3
28938-3	101 plus 770 uncured	0.9	0.8	2.2	3.2	5.7	8.2	7.0	8.5	10.8	13.3	15.9	19.5	22.7	26.3	29.4	32.5	35.7	38.9
28938-4	101 plus 770 uncured	1.0	1.4	2.8	4.0	6.2	9.0	7.3	9.0	11.3	13.8	16.6	20.3	23.0	26.8	29.8	30.7	35.8	38.8
29208-7A	101 plus Naugard	0.1	2.8	4.9	5.7	6.1	8.5	8.5	8.4	9.1	9.4	10.0	9.9	10.5	10.8	11.2	11.3	11.6	11.5
29208-8B	101 plus Naugard	0.2	2.7	4.4	5.8	5.8	8.4	8.9	8.3	9.1	9.5	10.0	10.0	10.4	10.7	11.1	11.2	11.6	11.4
29208-9C	101 plus Z6030	-0.5	-0.7	-0.6	0.1	-0.5	1.3	1.8	0.6	0.8	0.6	0.7	0.5	0.6	0.7	0.8	0.9	0.9	0.6
29208-10A	101 plus Z6030	-0.3	-0.3	0.3	0.1	-0.7	1.1	1.8	0.5	0.8	0.6	0.7	0.5	0.6	0.6	0.8	0.8	1.1	0.5
	"TBEC Formulations (3)																		
28937-1	TBEC/Solatex II	0.0	1.2	1.2	0.1	1.8	3.2	1.8	2.0	1.8	4.1	5.5	7.7	10.1	12.9	15.5	18.5	21.3	24.2
28937-2	TBEC/Solatex II	0.3	0.6	1.2	0.5	1.7	4.1	1.8	2.0	1.8	3.4	4.5	6.3	8.3	10.7	12.6	15.1	17.4	20.4
28937-3	TBEC/Starphire	-0.4	0.1	0.2	-0.3	0.8	2.5	1.3	1.8	2.9	3.5	3.8	4.7	5.8	7.4	8.7	10.4	12.5	14.2
28937-4	TBEC/Starphire	-0.3	0.1	0.3	-0.5	0.7	2.4	1.2	1.8	2.4	4.0	3.7	5.0	6.4	8.4	10.0	11.9	14.2	16.7
28937-5	TBEC/Solite	0.2	1.0	1.2	0.4	1.7	2.3	2.1	2.4	2.7	3.5	3.8	4.7	5.8	7.4	8.7	10.4	12.5	14.2
28937-6	TBEC/Solite	0.3	1.0	1.0	0.5	1.4	3.2	2.0	2.6	3.1	4.0	3.7	5.0	6.4	8.4	10.0	11.9	14.2	16.7
28937-7	TBEC/Tedlar cover	-0.0*	-0.3*	-0.3*	-0.3*	0.0*	2.5*	0.5*	0.9*	0.7*	1.1*	1.1	1.1*	1.2*	1.6*	2.3*	1.8*	2.2*	2.3*
28937-8	TBEC/Tedlar cover	0.0*	-0.5*	-0.7*	-0.8*	-0.3*	2.5*	0.4*	0.5*	0.5*	0.6*	0.7*	1.1*	1.3*	2.1*	2.4*	2.1*	2.4*	2.6*
28937-9	TBEC/Airphire	0.3	1.6	1.5	0.7	2.0	4.0	2.4	2.3	2.5	2.9	2.9	3.2	3.4	3.8	3.7	3.7	3.8	4.0
28937-10	TBEC/Airphire	0.8	1.7	1.6	1.1	2.0	4.7	2.3	2.4	2.2	2.3	2.2	2.5	2.5	2.9	2.7	2.6	2.8	3.0
29209-3	15295 no Naugard/Airphire	1.5	1.8	1.0	2.5	3.8	2.3	2.6	2.5	2.7	2.3	2.5	2.4	2.8	2.7	2.9	2.5	3.1	2.7
29209-4	15295 no Naugard/Airphire	1.2	2.0	1.2	2.7	4.1	3.1	3.3	3.2	3.4	3.0	3.2	3.4	3.8	3.7	3.8	3.7	4.3	4.3
29230-1A	TBEC/Solarex II	0.2	1.0	1.1	1.1	1.3	1.3												
29230-2B	TBEC/Solarex II	0.1	1.1	3.4	1.1	1.3	1.5												

Table 4: Average Yellowness Index (2) of Cured Laminates After EMMA(1)

Samples	Construction of Lam	week 0	week 4	week 12	week 36	week 40	week 48	week 61	week 65	week 69	difference 0 to 69 W
1, 2	Solite/A9918P	-1.3	0.5	1.6	13.8	21.1	30.3	34.1	34.5	34.7	36
3, 4	Solatex II/A9918P	-1.2	0.0	-0.0	1.0	1.3	1.3	0.6	0.6	0.8	2.0
5, 6	Starphire/A9918P	-1.6	-0.7	1.1	15.7	23.2	30.7	32.7	33.1	34.0	35.6
7, 8	Tefzel/A9918P	-0.1	-0.6	-0.9	-0.9	-0.9	-0.9	-1.1	-1.3	-1.1	--
9, 10	Solite/15295P	-2.6	-1.4	-1.0	-0.7	-0.0	2.3	3.9	4.2	4.8	7.4
11, 12	Solatex II/15295P	-2.3	-1.9	-2.0	-1.5	-2.1	-1.5	-1.8	-2.0	-1.8	0.5
							Difference 0 to 40				
new	Starphire/X9903P	-1.4	-1.7	-1.7	-	-1.5	--				

(1) EMMA Aging by DSET Laboratories, Phoenix, nominal 5 suns in U.V. region

3.0 DEFINE POSSIBLE DEGRADATION MECHANISMS

3.1 Purpose

Task 3 involved instrumental analysis and polymer characterization to verify suspected chemical degradation mechanisms. Both field-aged and laboratory Weather-O-meter-aged EVA-based encapsulant-containing modules and laminates were evaluated by a variety of analytical methods including GC/MS (gas chromatography/mass spectrometry) for UV absorbers, GC, FTIR (fourier transform infrared spectroscopy) for unsaturation and evidence of oxidation, thermogravimetric analysis for vinyl acetate content of the EVA, DSC (differential scanning calorimetry) for residual peroxide, and microscopy for morphological changes.

This task was performed with assistance from the University of Connecticut, Institute of Materials Science, Storrs, CT.

3.2 Conclusions

The following summarizes conclusions drawn from the work. A detailed Task 3 report on this effort was prepared and submitted to NREL February 6, 1995:

3.2.1: We have been unable to verify that discoloration of EVA-based encapsulant in photovoltaic modules is related to long chains of conjugated unsaturation (i.e. polyenes).

a. Infrared spectroscopy does not indicate the presence of significant amounts of unsaturation in discolored encapsulant. IR spectra of unaged encapsulant and highly discolored EVA-based encapsulant were practically superimposable with no perceptible absorption in the region of the spectra where double bonds would have been expected to have absorbed.

b. Vinyl acetate contents of all samples of encapsulant analyzed, which included both A9918P and 15295P grades, field aged and Xenon-Arc Weather-O-Meter aged, and all levels of discoloration, were virtually identical and at expected levels (see Table 5). Consequently, there appears to be little double bond formation from photolysis of vinyl acetate. And if there is little basis for double bond formation at any level, there is even less reason to expect conjugated double bond sequences of eight or more as would be required to develop color in the EVA copolymer.

c. EVA samples without additives when laminated between low iron glass did not discolor on exposure in the Ci35A Weather-O-Meter.

d. It is difficult to envision generation of chains of conjugated unsaturation containing more than eight double bonds and in sufficient quantity so as to result in the degree of discoloration that has been evidenced, especially at Carrizo Plains. After all, Elvax 3185 contains only 15 mole percent vinyl acetate and 85 mole percent ethylene, and the reactivity ratios for ethylene and vinyl acetate favor a completely random copolymer.

e. When treated with peracetic acid, discolored EVA-based encapsulant did not lose any of its color. But a PVC control, which had been purposely degraded to create conjugated unsaturation and a dark brown, nearly black color, was bleached to a translucent white when this conjugated unsaturation was oxidized by peracetic acid using the same method. Once again, this confirms that the brown color in field aged EVA-based encapsulant arises from some other cause than polyenes.

3.2.2: Unreacted Lupersol 101 peroxide remaining after curing exhibited a significant effect on concentrations of stabilizing additives on exposure to UV.

a. Cyasorb UV 531 concentrations suffered little reduction in concentration when a glass/encapsulant/glass laminate of A9918P without Lupersol 101 was Weather-O-Meter exposed for ten weeks,

whereas samples with usual amounts of Lupersol exhibited a 40% reduction in Cyasorb UV 531 concentration during twelve weeks Weather-O-Meter exposure. Also, the latter showed significant yellowing, while the former did not.

b. The concentration of Tinuvin 770 behaved similarly showing 61% reduction during twelve weeks Weather-O-Meter exposure.

3.2.3: Transformation products of BHT, Cyasorb UV 531, and nonyl phenol (from reactions of Naugard P), arising from reactions with alkoxy radicals from photolysis of Lupersol 101, might play an important role in discoloration of EVA-based encapsulant. Investigations with laboratory Weather-O-Meter aged glass/encapsulant/glass laminates showed correlation between color development and stabilizing additives/Lupersol 101 interactions (Table 6).

3.2.4: IR evidence indicates light colored encapsulant areas of modules recovered from the field have experienced oxidation. This suggests the backing is permeable to oxygen which diffuses into the rear of the modules and migrate through regions where there are no silicon cell barriers. Regions reached by oxygen might be "photo-oxidatively bleached." Colorless regions in the vicinity of cracks in the cells exhibit this same phenomenon, that is, the cracks provide access of oxygen to discolored encapsulant above the cells (Figures 12 through 14).

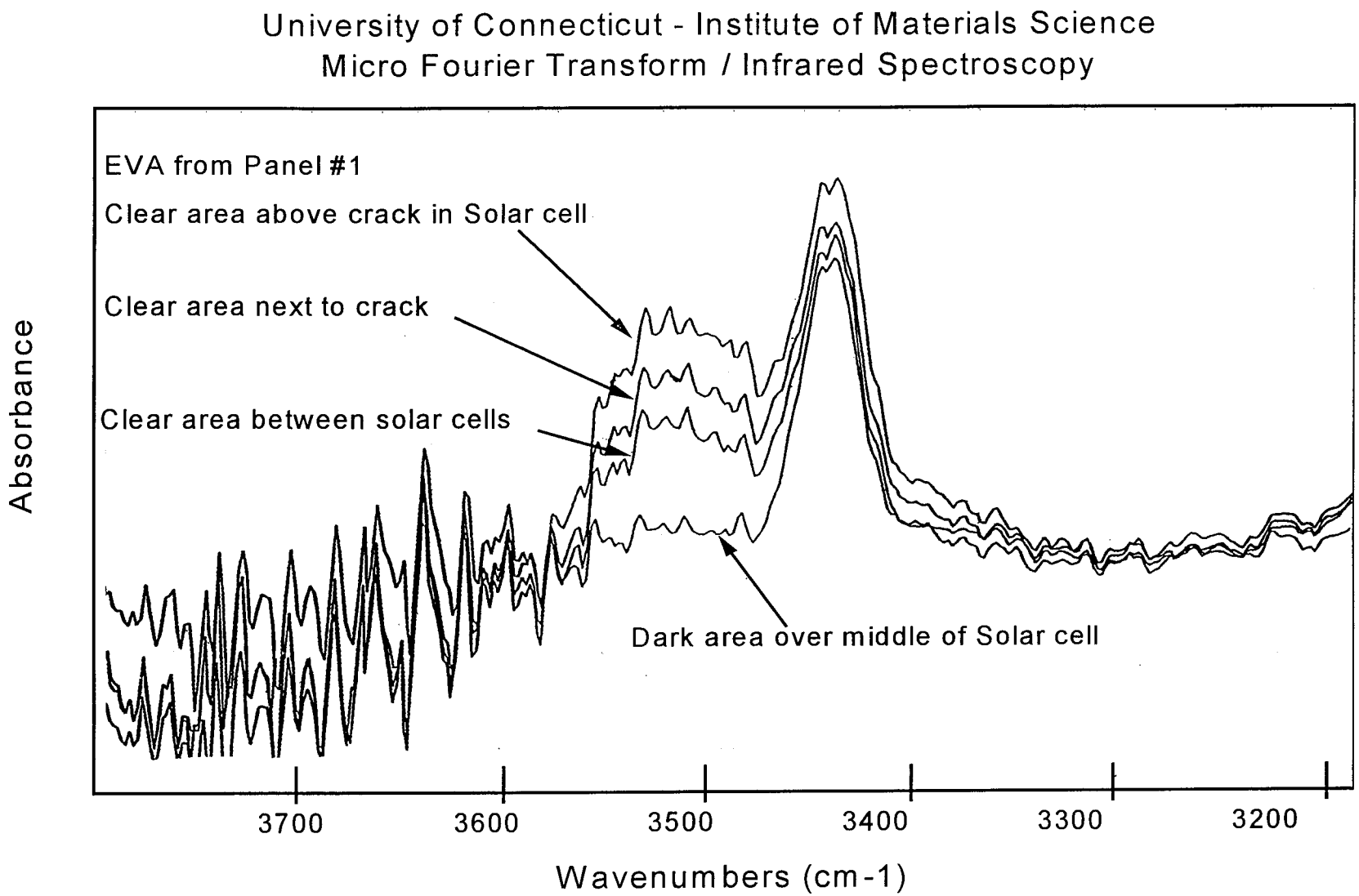

Figure 12 - University of Connecticut - Micro Fourier Transform/Infrared Spectroscopy

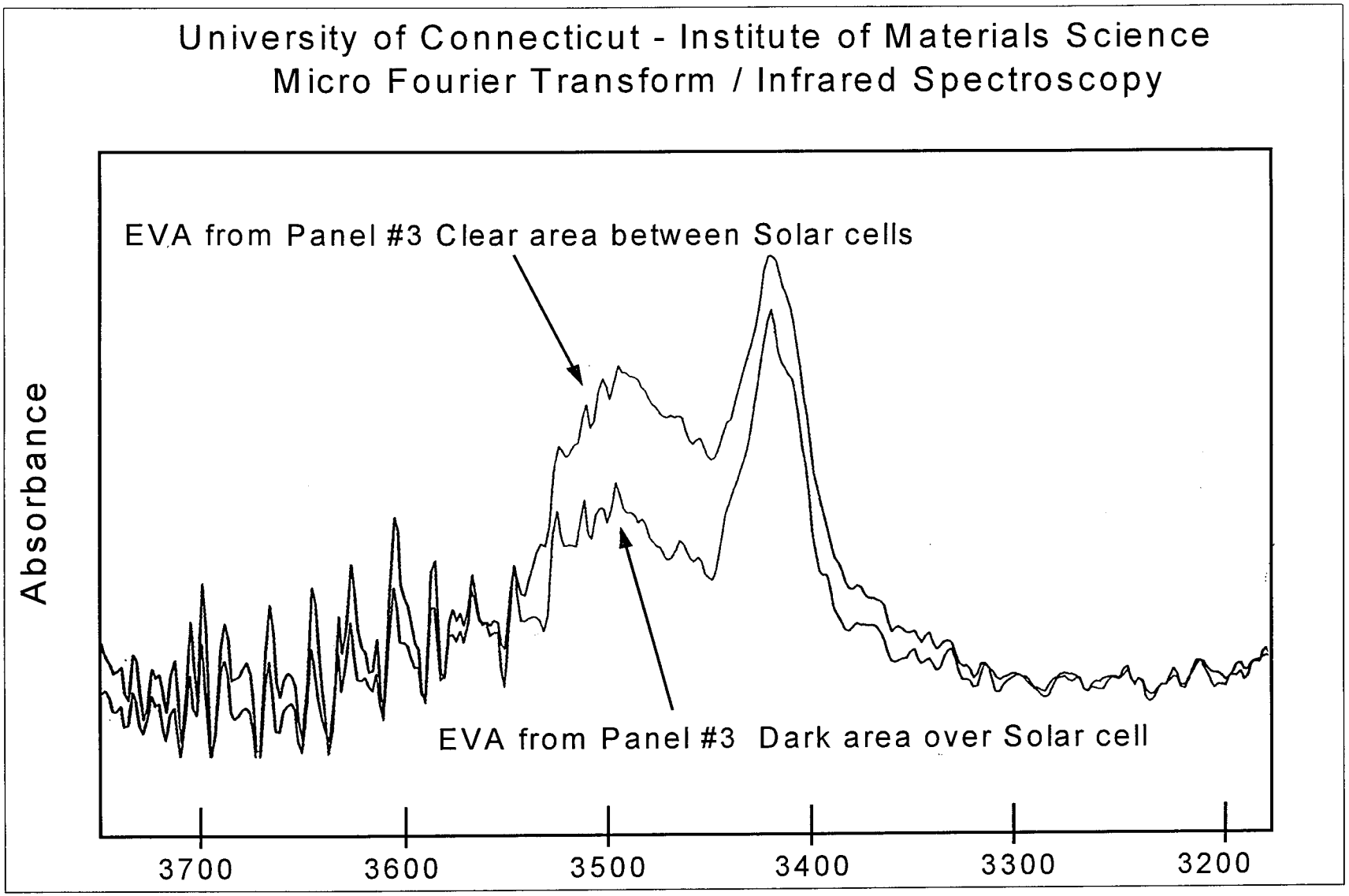

Figure 13 - University of Connecticut - Micro Fourier Transform/Infrared Spectroscopy - Panel 3

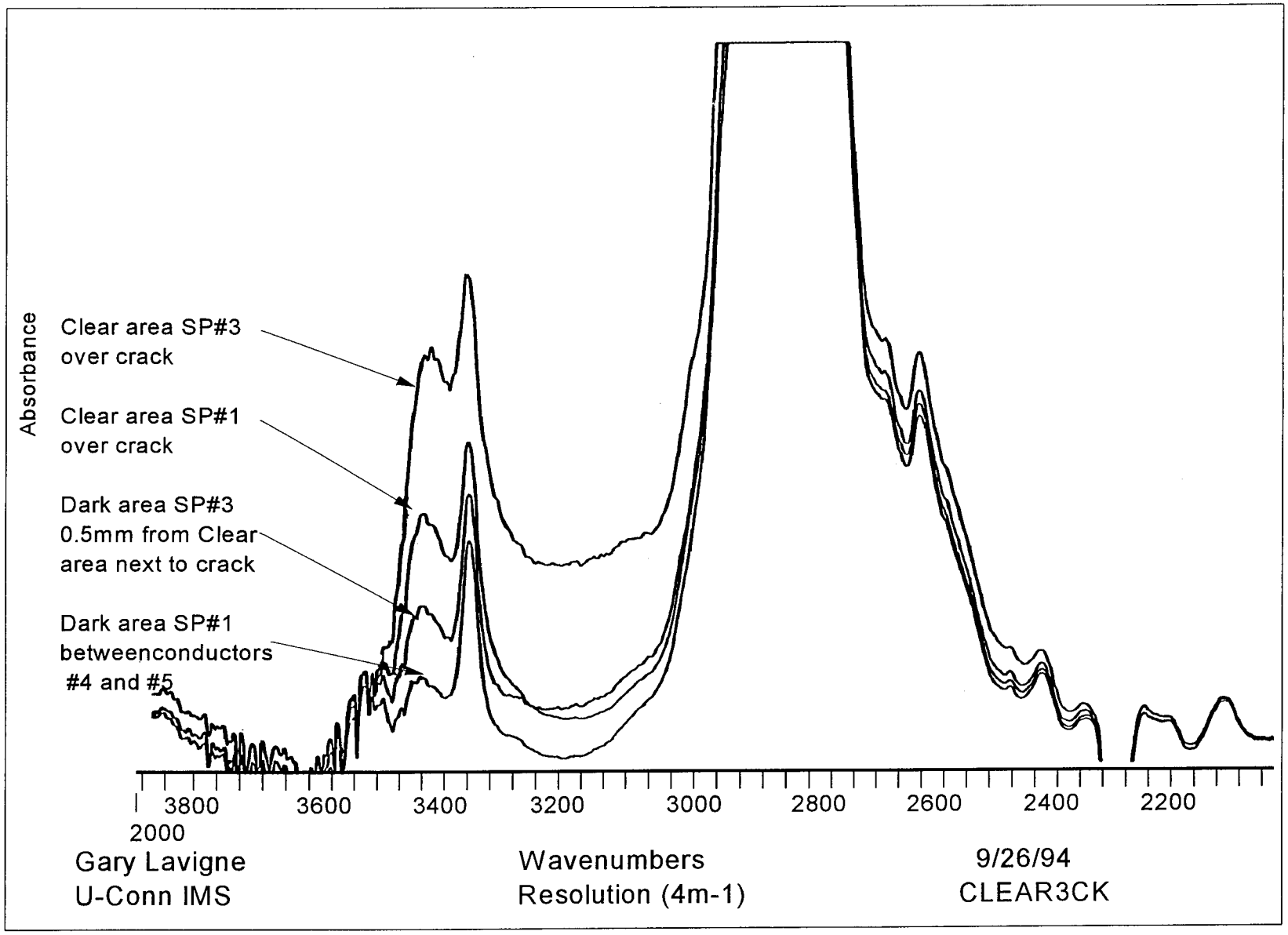

Figure 14 - IR Spectra of Encapsulant from Browned Modules

Table 5 - Analysis of EVA Encapsulants Shows No Significant Loss of Acetic Acid

% VINYL ACETATE CONTENT BY TGA (1)

Standard Cure A9918P		**Fast Cure 15295P**	
Description	**% VA (2)**	**Description**	**% VA (2)**
Uncured sheet	33.2	Uncured sheet	32.4
Cured, unaged	34.9	Cured, unaged	32.8
Weather-O-Meter aged, 12 weeks (light yellow)	33.5	Weather-O-Meter aged, 25 weeks (yellow)	32.1/32.6
Carrizo modules (brown)	33.9 to 33.5	Weather-O-Meter aged 34 weeks (amber)	33.0/33.6
DuPont value for virgin 3185	33.0		

(1) By complete thermolysis of the acetate group: ± 0.5%
(2) Corrected for ash residue

Table 6 - Cyasorb UV531, Tinuvin 770 and Lupersol 101 Content of Glass/EVA/Glass Laminated Uunaged and UV-Aged in Laboratory

			UV531		TINUVIN 770		LUPERSOL 101	
Sample No.	Composition and History	SL Yellow-ness Index	GC/FID area/mg x 10^{-4}	% Consumed	GC/FID area/mg x 10^{-3}	% Consumed	DSC joules/g	phr 101 Present
28950-2A	UV531 100% Std		6.20		8.88			
28950-4A	UV531 50% Std		2.38		9.44			
28948-9	Full Form, Unaged		5.17		9.39		3.47	0.11
29230-4	Full Form Aged 2 Wks		5.04	3 (rel. to 28948-9)	8.70	7 (rel. to 28948-9)	0.39	0.01
29227-4	101 Only, Unaged						3.16	0.10
29227-3	No 101, Unaged	0.5	5.30		17.1		0.72	0.02
29163-3	No 101, Aged 10 Wks	5.4	5.29	0	16.2	5		
29227-6	101 + UV531, Unaged	1.7	5.39				2.92	0.09
28208-5	101 + UV531 Aged 12 Wks	13.5	3.22	40				
29227-7	UV531 x 2, Unaged	0.6	13.4		10.6		2.01	0.05
28938-9	UV531 x 2 Aged 11 Wks	28.3	6.32	53	3.72	65		
29227-5	101 + 770 (no UV531) Unaged	0.5			9.18		2.76	0.08
29208-3	Aged 12 Wks	1			3.56	61		
29227-1	770 Only, Unaged	-0.3			14.9			
29203-6	Aged 6 Wks	-0.8			15.6	5		
29227-2	UV531 Only, Unaged	-0.2	5.99					
29203-11	Aged 11 Wks	-0.9	6.09	0				

4.0 TASKS 4 AND 5 DEVELOP ENCAPSULATION STRATEGIES FOR REDUCED DISCOLORATION AND/OR DEGRADATION AND CONDUCT ACCELERATED TESTING OF LAMINATES

4.1 Purpose of Tasks 4 and 5

Using results of Tasks 2 and 3, as discussed in sections 2 and 3 of this report, Task 4 and 5 activities sought to: 1) develop approaches for stabilizing EVA-based encapsulant against discoloration/degradation and consider alternate encapsulation systems that might be more inherently resistant to discoloration/degradation, and 2) evaluate performance of promising systems by AAS (accelerated aging studies) using Xenon-Arc Weather-O-Meter.

Stabilization strategies considered included: cerous and uranium salts as UVA (UV absorbers), metallocene compounds as UVA, other organic compounds with ability to strongly absorb radiation in the 285 to 350 nm range as UVA, other hindered amine light stabilizers (HALS) as alternatives to Tinuvin 770, higher concentrations of existing additives, alternate phosphites to and concentrations of Naugard P as peroxide decomposers, UV absorbing coatings on the glass superstrate, and UV-absorbing glass superstrates.

Also investigated were other low-cost polyolefin-based resins as alternatives to EVA.

4.2 Sample Preparation

Additives were compounded into Elvax 3185 and other base resins on a laboratory-sized, differential-speed, two-roll rubber mill. Sheet samples of these compounds were compression molded using laboratory hydraulic presses equipped with electrically heated platens.

Using these molded encapsulant sheets, glass/encapsulant/glass samples were prepared in a laboratory-scale laminator. These were prepared by vacuum lamination using commercial time/temperature/vacuum schedules recommended for encapsulation work when using either A9918P or 15295P, except when the cure schedule was purposely varied in order to assess its effect. A data logger and multiple thermocouples were used to verify temperature profiles of samples cured in the laminator. For most of this work, glass/glass laminates were used to facilitate visual, colorimetric, and spectrographic measurements.

4.3 Sample Evaluation

Coupon-size laminates were exposed to an irradiance of 0.55 watts per square meter per nm (measured @ 340 nm) in the Ci35A Weather-O-Meter using quartz/borosilicate glass filters. The nominal lower-end U.V. cut-off was 285 nm, and temperature and humidity were 100° C and >95%, respectively.

Samples were exposed for a minimum of 17 weeks or until significant degradation/discoloration of the encapsulant had occurred. In all cases, samples were exposed in duplicate.

Earlier calibration work on the Ci35A had revealed slight temperature and irradiance variations between locations in the top, middle, and bottom racks. Therefore samples were rotated between racks, from top to bottom on a weekly basis, to normalize any minor T/I differences.

Again, it should be emphasized that the Weather-O-Meter was used <u>only as a screening tool</u> - that is, a laboratory technique for preliminary comparative evaluation of various module encapsulation materials/constructions. There was no attempt to develop firm correlations between accelerated aging results and field information or to develop definitive acceleration factors, both of which are beyond the scope of this investigation.

On a weekly basis, samples were evaluated for Yellowness Index per ASTM D-1925. Selected samples were also checked periodically for percent light transmission (%T).

4.4 Results of Accelerated Aging Studies

With Task 2 and 3 work indicating an interaction of Lupersol 101 with stabilization additives as a key step in the mechanism of chromophore development, most of Task 4 focused on replacement additives. A number of alternate additives were evaluated in Elvax 3185 in combination with Lupersol 101 or Lupersol TBEC.

Glass/encapsulant/glass laminates were subjected to AAS as before. Starphire was used as the superstrate because Solite material (i.e., circa mid 1980s, representative of glass used for modules which have shown discoloration in the field. Both Solite and Starphire are non-cerium oxide, low iron glasses and have similar spectral transmissions.) is no longer available.

Numerous additives were evaluated in both "standard" cure and "fast" cure EVA-based formulations. Included were ten U.V. absorbers, ten hindered amine light stabilizers (HALS), and thirteen other stabilizers and antioxidants. These represented a variety of different chemical classes and manufacturers.

On the basis of these investigations, Springborn Testing and Research, Inc. developed four experimental formulations, X9903P, X9923P, and X9933P, encapsulants which cure under the same conditions as A9918P; and X15303P, a material which cures under the same conditions as 15295P. After 22 weeks in the Ci35A glass/encapsulant/glass laminates prepared with all four new encapsulants showed no more than a 4.8 increase in Yellowness Index (Table 7), while control laminates prepared with A9918P and 15295P exhibited Yellowness Index increases of 53.6 and 40.3, respectively. Again, it should be noted that all four experimental materials were laminated with Starphire glass, which is slightly more transparent to UV-B than Solite glass and thereby represents a "worst-case" for simulating outdoor exposure. Also, all four experimental grades are based on the same Elvax 3185 EVA resin used in 15295P and A9918P.

Experimental formulations in glass/encapsulant/glass laminates were also subjected to EMMA aging (Equatorial mount with mirror for acceleration; DSET Laboratories, Phoenix, AZ, nominal 5 U.V. suns).

As noted earlier, we also discovered that low-iron glass with small amounts of cerium oxide, when used as the superstrate, greatly reduces encapsulant discoloration. Not only does the cerium oxide-containing glass significantly reduce discoloration of existing formulations, such as A9918P and 15295P, when exposed in the Weather-O-Meter, it also further reduces yellowing of the experimental encapsulants.

Low iron glasses used in Tasks 4 and 5 included Solite (AFG - samples from the mid 1980s), Starphire (PPG), Solatex II (AFG - containing cerium oxide), and Solarphire (formerly Airphire: PPG - also containing cerium oxide). Solarphire (Airphire) and Solatex II benefit this application by removing most UV-B radiation between 280 and 330 nm, a region known to be detrimental to polymer stability (see Figure 15; Annual report under this subcontract, for the period December 30, 1992 to March 31, 1994 for further details on these glass superstrates).

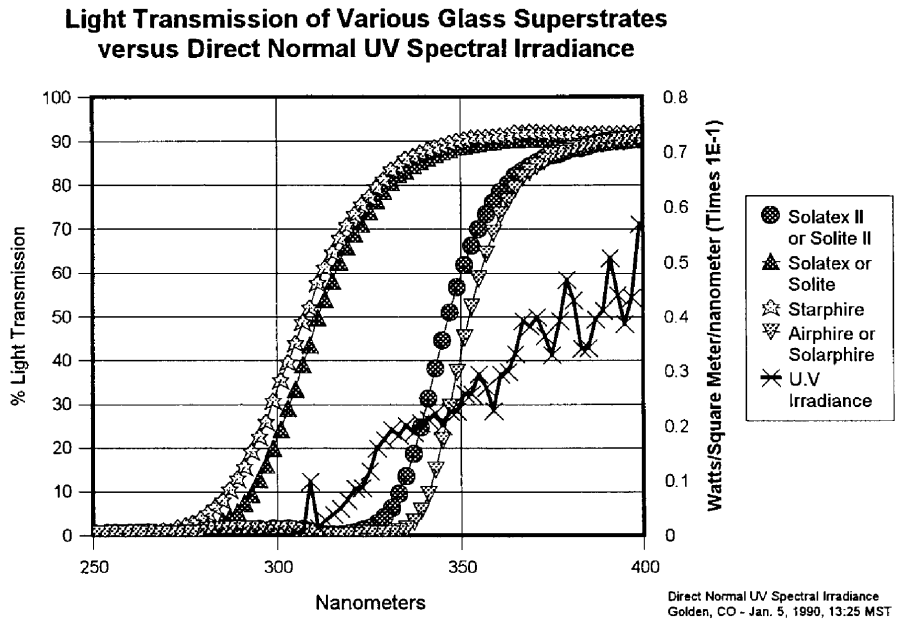

Figure 15 - Light Transmission of Various Glass Superstrates vs. Direct normal UV Spectral Irradiance

After 17 weeks of Weather-O-Meter aging, some significant differences in discoloration showed up in samples of A9918P using different types of glass superstrate. Solarphire (formerly Airphire) appeared the most effective at slowing discoloration (Yellowness Index of 9.3 at 17 weeks), but Solatex II was also very effective (Yellowness Index of 9.8 to 10.3), and results between these two glasses may be within experimental error. After 32 weeks aging, the Solarphire (Airphire)-covered laminate had a Yellowness Index of 17.8, while the sample prepared with Solatex II developed a Yellowness Index of 23.8.

It should be noted here that we have not attempted to establish the concentration of cerium-oxide in Solatex II or Solarphire, and of course no effort has been made to optimize the cerium-oxide level in order to provide the best encapsulant protection. From curves of spectral transmission versus cerium-oxide content for a series of glass samples, we estimate that Solatex II and Solarphire contain between 0.3% and 1.0% cerium-oxide.

By comparison, control Solite/A9918P allowed a 17 week Yellowness Index of 39.1 to 40.4, while encapsulant discoloration with Starphire superstrate was somewhat worse, with a Yellowness Index of 48.7 to 49.6. After 35 weeks in the Ci35A, the Solite-covered sample showed a Yellowness Index of 81.9, compared with 17.8 to 23.8 for samples prepared with cerium-oxide containing glass, as noted in the preceding paragraph.

It is noteworthy that Starphire transmits more light in the 280 to 320 nm wavelength region than does Solite, and this could account for the difference in discoloration rate (see Figure 15).

We found that use of certain cover films was also a viable stabilization strategy.

When an oxygen permeable substrate or superstrate was used in place of one layer of glass, comparatively little color development occurred. For example, A9918P-based laminates prepared with Solite glass and no backing showed a Yellowness Index, after 17 weeks of Weather-O-Meter aging, of only 3.1 to 3.3 and only 4.5 after 26 weeks. Also, samples prepared with 10 mil Tedlar backing, had no visible discoloration after 17 weeks of aging.

More significantly, however, when Tedlar or Tefzel was used as superstrate, with low iron glass as substrate and A9918P as encapsulant, Yellowness Index readings were only 2.0 to 2.9 after 17 weeks in the Weather-O-Meter. And after 32 weeks, the Tefzel-covered sample had a Yellowness Index of only 3.9.

Analytical work on encapsulant from fielded modules, reveals that oxidation is taking place in the encapsulant in such permeable areas, and we speculate that either chromophores are being oxidized as well, or their formation is being inhibited by oxygen.

4.5 Outdoor EMMA Accelerated Weathering Tests

For added confirmation of laboratory accelerated aging data based on Atlas Ci35A xenon-arc Weather-O-Meter exposure, selected samples were submitted to DSET Laboratories Inc., Phoenix, Arizona, where they were subjected to EMMA (Equatorial Mount with Mirrors for Acceleration) accelerated outdoor exposure. Samples, prepared in duplicate, include:

Solite (circa 1980s)/A9918P/Starphire (substrate) - CONTROL

Solatex II/A9918P/Starphire

Tefzel/A9918P/Starphire

Starphire/A9918P/Starphire

Solite (circa 1980s)/15295P (with Lupersol TBEC)/Starphire - CONTROL

Solatex II/15295P/Starphire

Solite/A9918P/cells/Tedlar film laminate

Starphire/X9903P/Starphire - NEW "STANDARD-CURE" ENCAPSULANT

These samples were evaluated monthly by DSET Labs for Yellowness Index (see Table 4). Control material A9918P with either Solite or Starphire glass superstrate developed significant yellowing (i.e., a Yellowness Index increase of 35.6 to 36.0 after 69 weeks , or 78,310 MJ/m^2 of exposure).

In comparison, the same A9918P encapsulant when laminated with Solatex II superstrate developed a Yellowness Index change of only 2.0 after 69 weeks or 78,310 MJ/m^2 exposure.

With a breathable superstrate, Tefzel film, A9918P developed no color after 78,310 MJ/m^2 exposure. Once again, any chromophores developed were presumably photobleached by available oxygen.

As expected, "fast cure" 15295P when laminated with Solite glass discolored at a significantly slower rate than did A9918P, with a Yellowness Index change of 7.4 versus 36.0 after 69 weeks. And when "fast cure" encapsulant was covered with Solatex II and exposed to EMMA for 69 weeks (78,310 MJ/m^2 exposure) there was negligible color development (0.5 Yellowness Index).

Finally, after 40 weeks of EMMA 47,420 MJ/m^2 exposure under a Starphire superstrate, experimental "standard-cure" encapsulant X9903P developed almost no measurable color.

Table 7 - Average Change in Yellowness Index of Cured Glass/EVA/Glass Laminates With Weather-O-Meter Aging (1)

Sample Construction (2)	Change in Yellowness Index 4 weeks	8 weeks	12 weeks	24 weeks
"Standard Cure" Encapsulants				
X9903P/Starphire	2.4	2.1	1.6	2.0
X9933P/Starphire	2.8	4.3	5.3	4.3
X9923P/Starphire	1.8	2.0	--	1.0
A9918P/Starphire (Control)	6.3	16.0	29.9	58.8 (4)
A9918P/Solatex II or Airphire	5.6	6.8	8.0	12.6
"Fast Cure" Encapsulants				
X15303P/Starphire	2.1	1.9	0.9 (3)	2.0
15295P/Starphire (Control)	0.8	2.6	6.1	48.9
15295/Solite (Control)	1.7	2.7	5.8	31.2
15295P/Solatex II	1.3	1.8	2.2	4.8

(1) Ci35A xenon-arc Weather-O-Meter, 100° C, 0.55 watts/square meter at 340 nm

(2) Glass/EVA/Glass laminates with Starphire on the back side

(3) Data taken by different technician

(4) Solite glass superstrate

5.0 TASK 6: PREPARE PILOT SCALE QUANTITIES OF PROMISING ENCAPSULANTS

5.1 Purpose of Task 6

This task involved extruding the four promising experimental EVA-based encapsulants into thin sheet of required size and quantity for module manufacturer team members to prepare coupon-size mini-modules for accelerated aging and full size modules for qualification testing and field testing.

5.2 Extrusion Trials

Four experimental grades, X9903P, X9923P, X9933P, and X15303P, were prepared using the same production methods as normally used for A9918P and 15395P. "Virgin" Elvax 3185 EVA pellets were dry blended with appropriate additives and extruded into 0.018 inch thick sheet. Width and texture were per team members' requirements. Extrusion conditions were the same as those used for A9918P and 15295P commercial production.

A schematic diagram of a typical single-screw extruder appears in Figure 13. Pellets are fed to the hopper on the left where a cooling jacket prevents premature melting of the resin. Such melting can cause bridging or melt blocking which can interrupt the flow of material.

Resin travels through the barrel from left to right. The turning screw both advances and compresses the material, while heating zones on the barrel ramp the temperature up from ambient to the desired melt temperature.

A screen pack at the end of the barrel removes most gels and other contamination. A static mixing element was employed after the screen pack. To ensure thorough blending of resin and additives. Melt then passes downward through a sheet die onto a series of polished rolls which cool and calender the sheet.

Blends were extruded at STR using a Hartig 2.5 inch, 24:1 L/D single screw extruder, sheet die, roll stand and take off system. Sheet was wound with release paper and put up in nominal 40 pound rolls. Each roll was packed in foil and black polyethylene bag , placed in a shipping container, and sent to the team member.

5.3 Results

Experimental materials were extruded with no difficulty and processed and handled essentially as their A9918P "standard cure" and 15295 "fast cure" counterparts. Appearance and surface character also seemed no different.

Rolls were shipped to the following team members: ASE Americas, Inc.; Astropower Inc.; EBARA Solar, Inc.; Global Photovoltaic Specialists, Inc.; Photocomm, Inc.; Siemens Solar Industries; Solarex; Solec International, Inc.; and United Solar Systems Corp.

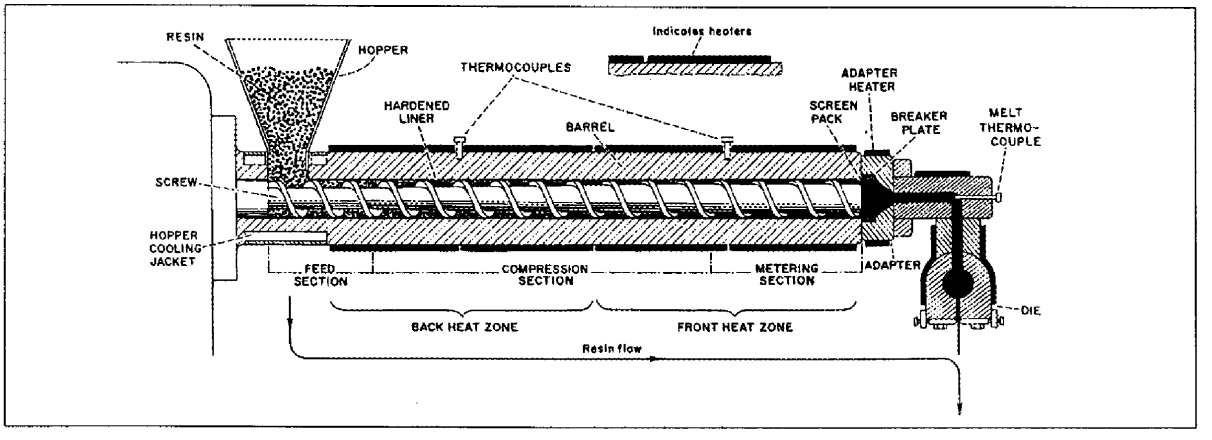

Figure 16 - Cross Section of Typical Extruder

6.0 TASK 7: TEST TEAM MEMBER-PREPARED MINIMODULES

6.1 Purpose of Task 7

The intent of this effort was to evaluate discoloration resistance of experimental encapsulants in constructions representative of full size modules. Prior testing had only been done between glass coupons or between Tefzel/glass. This Task 7 accelerated aging in a Xenon Arc Weather-O-Meter allowed us to determine, relatively quickly, any interactions between encapsulants and typical cells, interconnects, and backing materials.

6.2 Testing Method

Minimodules measuring 2.75 x 2.75 inches and 2.75 x 5.5 inches were received from several team members, including EBARA, USSC, ASE/Americas, Solarex, Siemens Solar, Solec International, and Photocomm. Single-cell or half-cell constructions were typical; each minimodule had leads through the backing material. Encapsulants included four experimental materials plus controls A9918P and 15295P. Glass superstrate was either Solite II (cerium glass from AFG) or Starphire (low iron/non-cerium type from PPG).

Minimodules were connected to 1 ohm resistors, to provide fixed loads, and placed in metal Weather-O-Meter sample holders. Eighth inch thick polypropylene spacers and thin sheets of Mylar polyester were used behind the minimodules to isolate leads and resistors from the holders.

Weather-O-Meter aging was conducted at the same irradiance as in Task 5, 0.55 watts/m^2/nm at 340 nm, but at a lower black panel temperature. A blackpanel temperature of approximately 84° C provided a temperature over the cells of approximately 90° C.

Minimodules were inspected weekly at first, and then every other week, for any discoloration, delamination, cell/interconnect/encapsulant chemical interactions, etc. Of course, with cells in place, it was not possible to determine Yellowness Index for these samples.

In addition, sixteen 2.75 x 5.5 inch minimodules, representing several different encapsulants/ constructions, were sent to DSET Labs in Phoenix where they are being exposed to EMMA (equatorial mount with mirrors for acceleration) accelerated outdoor aging at a nominal 5 U.V. suns. Results on these samples will not be available until early in 1998.

6.3 Results of accelerated aging

Minimodules were examined visually after 26 weeks (Table 8). Samples from two manufacturers went into the Weather-O-Meter nine weeks later than the first three sets, and Table 8 also provides observations on those minimodules after 17 weeks. Because of the small size, no effort was made to evaluate IV curves for these samples. It simply was not possible to measure with the precision needed to distinguish between minimodules.

<u>A9918P Control:</u> In Table 8, observations are organized by manufacturer and by encapsulation system. For control minimodules with A9918P from team members A, D, and E, encapsulant over the cells exhibited classical browning phenomenon. We suspect that for minimodules from team member B, samples with A9918P and X9903P may have been reversed somehow.

Samples from team member C, which used Tefzel cover film, appear to have photobleached, as expected based on earlier Weather-O-Meter and EMMA studies on glass/encapsulant/Tefzel laminates (see sections 2.4.6 and 2.5 of this report).

Note that control A9918P-based minimodules from team member E, which were covered with Solite cerium-containing glass, showed no color change over the cell.

15295P with Cerium Glass: All samples prepared with the conventional fast cure encapsulant and covered with Solite cerium glass showed no discoloration whatsoever.

Experimental Formulations: Three of the experimental materials, X15303P, X9903P and X9923, fared quite well. All samples under glass superstrates remained unchanged over the cells, with the exception of X9903P for team member B. Again, we suspect that X9903P and A9918P samples may have been reversed.

The one surprise in this series was browning of three of the experimental encapsulants under Tefzel cover film. Since there is available oxygen in these systems, we suspect that a different browning mechanism may be taking place than under glass superstrates. Two observations support a difference: 1) browning occurred much more rapidly than with A9918P under glass, and 2) A9918P under Tefzel showed no browning after 26 weeks which is consistent with what we observed for Tefzel/glass laminates exposed in both Weather-O-Meter and EMMA.

In our proposal for this PVMaT program, we had suggested a "family of stabilization strategies" which would be adaptable to various module construction. While the experimental EVA-based encapsulants appear promising for modules with glass superstrates, in the case of Tefzel cover film the conventional A9918P or 15295P would be preferred.

Table 8 - Effect of Weather-O-Meter (1) Aging on Mini-Modules (2)

BROWNING OVER THE CELLS

AFTER 26 WEEKS EXPOSURE

Mini-Module Construction (includes cells)
***

Module Mfg.	A9918P/Starphire		15295P/Solite		X9903P/Starphire		X9923P/Starphire		X9933P/Starphire		X15303P/Starphire	
A	dark brown over cell		N.C. looks very good!		N.C. looks good		N.C.		medium brown		N.C. looks good	
B	N.C. (1)		N.C. Looks very good!		light brown (1)		brown only at edge of Cu back cell		brown at Cu cell edge migrated ov back a bit		N.C. looks very good!	
C**	N.C. looks good		N.C. Looks very good!		quite brown		dark brown		very slight grid line yellowing		quite brown	
AFTER 17 WEEKS												
D*	medium brown		N.C. looks very good!		N.C. looks good		N.C.		very lgt. brown		N.C. looks very good	
	Starphire	Solite***	Starphire	Solite***	Starphire	Solite***	Starphire	Solite***	Starphire	Solite***	Starphire	Solite***
E	lgt. brown	N.C.	N.C.	N.C.	N.C.	N.C.	N.C.	N.C.	med.	N.C.	N.C.	N.C.
			looks very good!		looks very good!		looks very good!				looks very good!	

* Glass/glass modules

** Tefzel cover film

*** Cerium glass

1) suspect A9918P & X9903 P may have been mixed up

(1) Ci35A, approx. 90 deg. C over cells, 0.55 W/sq. m. at 340 nm, continuous

(2) cells wired to 1 ohm resistors

7.0 QUALIFICATION TESTING OF FULL SIZE MODULES

7.1 Task 8 Qualification Tests per IEEE 1262

7.1.1 Purpose of Task 8 Qualification Tests: The IEEE 1262, "Recommended Practice for Qualification of Photovoltaic (PV) Modules," protocol was developed to assist in evaluating flat-plate PV module design performance, safety, and susceptibility to known failure mechanisms. This "recommended practice" emphasizes testing for potential degradation of module performance resulting from environmental weathering, mechanical loading, corrosion, and shadowing.

The intent of Task 8 was to determine the impact of experimental encapsulant formulations on module performance.

7.1.2 Testing Methods: Given promising accelerated weathering results obtained with experimental encapsulants - X9903P, X9923P, X9933P, and X15303P - all four were included in module testing tasks, rather than two systems as originally proposed.

Fresh pilot quantities of the four encapsulants were extruded and shipped to team members during May 1996. Module makers used these materials to prepare full size modules for qualification testing and field testing. Preferred dimensions for these modules were 16 x 47 inches, with 20 x 52 inches being a maximum. Modules were to be a nominal 50 watts and representative of normal production.

Team members providing modules for qualification testing included ASE/Americas, Astropower, Photocomm, Siemens, Solarex, and Solec International. Modules were prepared in sets of six, according to the summary in figure 14. All modules were shipped directly to the Photovoltaics Testing Laboratory at Arizona State University, Tempe where the tests were conducted.

MANUFACTURER	**A**	**B**	**C**	**D**	**E**	**F**	**TOTAL**
ENCAPSULANTS	**NUMBER OF MODULES**						
9903	6	0	6	6	0	6	24
9923	0	6	6	6	0	6	18
9933	6	6	6	6	0	6	30
15303	6	6	0	6	6	6	30
TOTAL	18	18	18	24	6	18	102

Figure 17 - Modules for Qualification Testing (IEEE 1262)

At the recommendation of ASU, testing was performed in accordance with the more stringent IEEE 1262 rather than NREL/TR-213-3624 as originally proposed. IEEE 1262 includes a damp heat (85° C/ 85% R.H.) exposure sequence. Testing included sequences A, B, and C (see figure 18) of the test program.

7.1.3 Qualification Test Results: A total of 102 modules underwent the IEEE 1262 tests. Out of each set of six modules, two each were subjected to sequences A, B, and C.

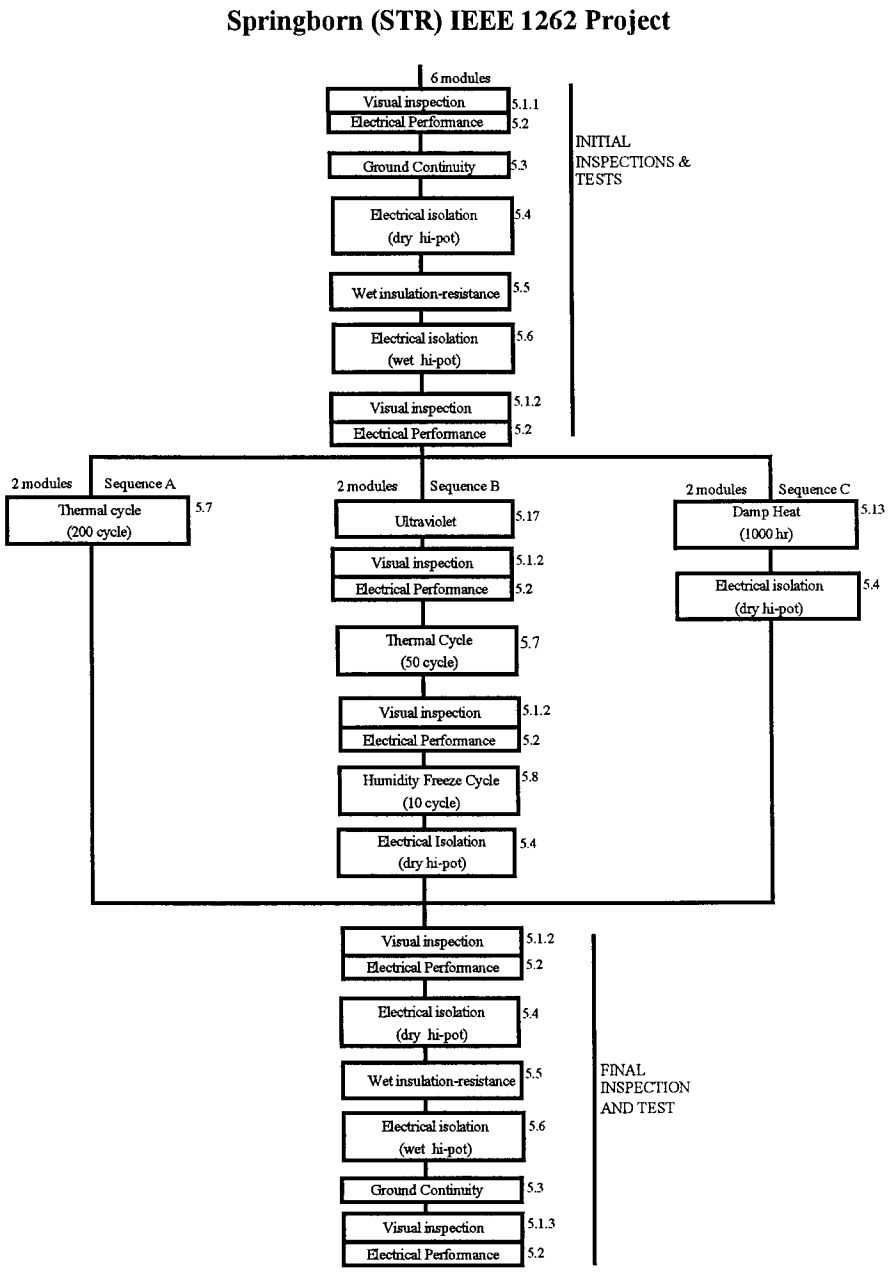

Figure 18 - Sequence of Qualification Testing per IEEE 1262

Of the 102 modules, 21 failed. However, all failures occurred in modules from two manufacturers with 15 of those from one manufacturer. Also, it is remarkable that excepting those modules with X9933P which turned yellow during damp heat, **there were no encapsulant-related failures!**

Appendix B provides a summary of abnormal test results. Most of these abnormalities did not constitute failures, but were simply noted during testing. For example, several modules exhibited bubbles in the encapsulant, but these occurred only in the modules of team members B and C and were likely due to processing conditions.

7.2 Degree of Cure of EVA-Based Encapsulants

7.2.1 Purpose of Cure Studies: The purpose of this subtask was to evaluate the degree of crosslinking of encapsulants in various modules. Gel content per STR TP 025 was used to determine if team member-to-team member processing variations and formulation-to-formulation differences had any effect on curing of experimental EVA-based encapsulants.

7.2.2 Test Method for Degree of Cure: A number of full size modules which had completed various qualification sequences were examined. On each module, the backing material or cover film as appropriate was peeled away and a small sample of cured encapsulant was recovered with a razor knife.

A one gram sample of encapsulant was carefully weighed and extracted in 60° C toluene for 20 to 24 hours in a sample jar with no agitation. The gel was then filtered through a tared filter paper, rinsed with more toluene and dried at 105° C. The sample was then reweighed and the percent EVA solids remaining was calculated, which is the gel content.

7.2.3 Gel Content Results: STR routinely performs gel content tests on cured samples of PhotoCap™ EVA-based encapsulants as part of its quality control. The minimum acceptable gel content is 65%; production lots of PhotoCap typically give gel contents of approximately 80%.

Test results on encapsulant samples from 20 different modules, representing four manufacturers and three experimental materials, appear in Table 9. With exception of encapsulants from two modules prepared with X9903P by team member E, gel contents of all were within acceptable range. The average gel content, not counting these two modules, was in excess of 80%, indicating a high degree of cure.

While the two modules from team member E prepared with X9903P had only 18 to 53% gel content, samples of this same encapsulant from modules prepared by two other team members had gel contents of 79.7% and higher.

On average X9923P gave the highest gel content (87.7%) and X9903P the lowest (81.6%). The differences are probably significant and likely result from differences in the cure chemistry for each.

7.3 Color Change Within Qual. Test Modules

7.3.1 Purpose and Method: Modules which had completed qualification testing were examined visually for any discoloration over the cells or between the cells. Specifically, we were looking for any differences between experimental encapsulants.

7.3.2 Color Change Results: The observations are summarized in Table 10. Over the cells there was no apparent color change in any of the modules. However, between the cells several modules exhibited a slight brown color.

Most of the discoloration occurred in modules prepared by team members E and F. Since the modules of other team members, prepared with the same encapsulants and subjected to the same testing sequences, did not discolor between the cells, it appeared that the browning was related to the backing material - in most cases white, either TPE or TPT type.

Backing material was carefully removed from the affected modules. It was noteworthy that modules exposed to IEEE 1262 sequence B (U.V. exposure) exhibited browning only between the cells while the backings of modules which underwent sequence C (damp heat; 85° C/ 85% RH) were found to discolor both between and behind the cells. This suggested that the browning was being induced not only by U.V. but also by elevated temperature alone. In other words, the effect could be thermal as well as photothermal.

It was beyond the scope of the program to undertake an exhaustive study of the backings, but some limited investigation was done. With the use of a razor knife, it was possible to separate the backing plies. Where the backing contained a clear polyester layer it was possible to see a brown residue, apparently the laminating adhesive, on both sides. This gummy brown material could be easily scraped off both sides of the polyester leaving the clear colorless polyester film.

Preliminary Infrared Spectroscopy indicates that the adhesive is some type of acrylic.

7.4 Qualitative Adhesion of Experimental Encapsulants to Various Substrates

7.4.1 Purpose: The goal of this subtask was to determine if environmental exposure, particularly Sequence C, "damp heat" of IEEE 1262 had an adverse effect on the adhesion of experimental encapsulants to backing materials, glass superstrates, cells, and leads and interconnects.

7.4.2 Experimental Method: Using a razor knife, a small area of the surface, back or front as appropriate, was scored and an edge of film or encapsulant teased loose or cut. This edge was then peeled slowly by hand or with the aid of pliers if the adhesion was very good. The adhesion was given a numerical rating as follows:

1 - excellent; cohesive failure within encapsulant or substrate

2 - very good; encapsulant can be peeled from substrate but with difficulty

3 - good; encapsulant can be peeled but with less difficulty

4 - fair; encapsulant can be peeled fairly easily

5- poor; little or no adhesion

It was beyond the scope of this study to develop quantitative adhesion results (e.g. peel testing).

7.4.3 Results: The adhesion ratings appear in Table 11, where they are organized by encapsulant type, module manufacturer, and then by IEEE 1262 testing sequence.

Glass superstrate: In general, adhesion to glass was good to very good and did not seem to be adversely effected, within the scope of the testing, by heat and moisture. Modules made by team member F appeared to have slightly better encapsulant/glass adhesion than the others. But, there seemed to be no difference in adhesion to glass for the three experimental encapsulants tested.

Cells: Overall, the best adhesion to a substrate was that of encapsulant to cell. With the exception of X15303P-containing modules by team member H, all had encapsulant/cell adhesions ranging from very good to excellent (i.e., cohesive failure).

Within the scope of this evaluation, formulations cured under standard conditions (X9903P and X9923P) appeared to have slightly better adhesion to the cells than did the experimental grade which cures under "fast-cure"

conditions (X15303P). But again, there appeared to be no adverse effect on adhesion of environmental exposure, especially damp heat.

Leads/Interconnects: Adhesion of encapsulant to leads/interconnects showed much more variability, ranging from fair to excellent. Most of the variation seemed to come between modules of different team members. This may relate to the type of metals and surface cleaning used.

Cover or backing films: In general, adhesion of encapsulant to films was good to excellent. The exceptions involved modules of two manufacturers, team members E and F, which had been subjected to 1000 hours of damp heat (85 /85% RH). Adhesion of encapsulant to film was only fair to poor in these cases.

It is noteworthy that modules which exhibited fair to poor encapsulant/film adhesions were the same ones that were slightly browned between cells. This suggests that loss of adhesion may have been due to the adhesive/tie layer on the backing laminate and not to the encapsulant itself. This is further supported by the fact that backings which did not discolor during damp heat showed no loss of adhesion between encapsulant/backing.

Table 9 - Qual Test Modules from ASU

% GEL CONTENT OF QUAL. TESTING MODULE ENCAPSULANTS

MODULE MFG.	Sequence X-9903P	A (T cycle) X-15303P	X-9923P	Sequence X-9903P	B (U.V.)/ X-15303P	T (cycle) X-9923P	Sequence X-9903P	C (dampT) X-15303P
"A"		83.1%				88.9%		
"E"	18.3%				86.4%		52.9%	77.9%
"F"	82.0%	76.8%		84.9%			84.6%	80.9%
"G"	84.6%	82.0%	86.0%	84.5%	85.6%	84.0%	79.7%	79.7%

	% GEL	Av. Dev.	Typical
All X9903P	83.4%	1.7%	80%
All X9923P	87.7%	2.7%	80%
All 15303P	81.6%	2.7%	80%

All Seq. A	82.4%	All Seq. B	85.7%	All Seq. C

Table 10 - Qual Test Modules from ASU

OBSERVATION ON QUAL TESTING MODULES OVER THE BACKING												
			QUAL. TESTING			SEQUENCES		PER IEEE 1262				
MODULE MFG.		Sequence **X-9903P**	A (T cycle) **X-15303P**	**X-9923P**		Sequence **X-9903P**	B(U.V./ **X-15303P**	T cycle) **X-9923P**		Sequence **X-9903P**	C(damp T) **X-15303P**	**X-9923P**
"A"	**	--	colorless	colorless		--	colorless	colorless		--	colorless	colorless
"D"	**	colorless	--	colorless		colorless	--	colorless		colorless	--	colorless
"E"	**	colorless	colorless	--		--	colorless	--		**slgt brown**	**slgt brown**	--
"F"		colorless	colorless	--		**slgt brown**	**slgt brown**	--		**slgt brown**	**slgt brown**	--
						between	**cells**			**behind & between cells**		
"G"	**	colorless	colorless	colorless		colorless	colorless	--		**slgt yellow**	--	**slgt yellow**
*	non-cerium low iron glass											
**	likely made with cerium glass(stiple pattern											
***	prepared with Tefzel											

Table 11 - Effect of Qual. Test Conditions (1) on Adhesion (2)

ENCAP. ADHESION RATING (2)

MFG.	S/N	QUAL. SEQUEN.	ENCAPS U.	TO GLASS	TO CELL	TO INTER.	TO COVER OR BACKING FILM
E	448	A	X9903P	2 TO 3	1	1	1 colorless
	452	C	X9903P	3	1 TO 2	1	**4 slgt brown**
F	32	A	X9903P	1 TO 2	2	3	1 TO 2 colorless
	34	B	X9903P	2	1	2 TO 3	2 colorless behind cell
	35	C	X9903P	1 TO 2	1 TO 2	3	**4 slgt brown**
G	02	A	X9903P	-	1 TO 2	3	1 colorless
	04	B	X9903P	-	1 TO 2	3	1 colorless
	05	C	X9903P	-	1 TO 2	3	1 slightly yellow
A	6	B	X9923P	2	2	2	3 colorless
	2	C	X9923P	2 TO 3	1 TO 2	3	3 colorless
G	22	A	X9923P	-	1 TO 2	4 TO 4	1 colorless
	26	C	X9923P	-	1 TO 2	3 TO 4	3 slightly yellow

(1) IEEE 1262: A=T cycle; B=UV; T cycle; C=85/ 85

(2) Qualitative: 1=excellent, 2=v. good, 3=good, 4=fair

EFFECT OF QUAL. TEST CONDITIONS (1) ON ADHESION (2)

Table 11 (continued - 2)

MFG.	S/N	QUAL. SEQUEN.	ENCAPSU.	TO GLASS	TO CELL	TO INTER.	TO COVER OR BACKING FILM
A	2	A	X15303P	2	2	3	3 colorless
	00140	B	X15303P	2	2	3	2 TO 3 colorless
	00145	C	X15303P	2 TO 3	2	3	3 colorless
E	458	A	X15303P	2 TO 3	1 TO 2	3	2 TO 3 colorless
	446	B	X15303P	2 TO 3	1 TO 2	2 TO 3	2 TO 3 colorless
	447	C	X15303P	2 TO 3	1 TO 2	**4**	**4 slgt brown**
F	22	A	X15303P	1 TO 2	2	3	1 TO 2 colorless
	26	C	X15303P	2	1 TO 2	3 TO 4	**4 TO 5 slgt brown**
G	12	A	X15303P	-	1 TO 2	3 TO 4	2 TO 3 colorless
	14	B	X15303P	-	1	3 TO 4	2 TO 3 colorless
H	22	A	X15303P	3	3	3	1 TO 2 - -
	26	C	X15303P	3	3	2	1 TO 2 - -

(1) IEEE 1262: A=T cycle; B=UV; T cycle; C=85/ 85

(2) Qualitative: 1=excellent, 2=v. good, 3=good, 4=fair

Table 12 - Full Size PV Modules Requested From Team Members For Qual Testing

					MODULES FOR FIELDING AT STAR					
			control	modules						
Encapsulant System			A9918P	A9918P	X9903P	X9923P	X9933P	15295P	X15303P	
			Cerium	Starphire						
Company			glass	glass	Cerium Glass or Tefzel Cover Film					
	width (in)	Length (in)								
B	20	20			none at this time					
G	17.8	39			2	2	2		2	
H	19.76	43.65						3	3	
A	13	51	6	6		2	2		2	
C	15	49			none at this time					
D	17.5	48			2	2	2	2		
F	20.75	47.25			2		2	2	2	
Preferred Size	16	47								
Maximum Size	20	52								
	NUMBER OF MODULES		6	6	6	6	8	7	9	
TOTAL NUMBER OF MODULES										**48**

8.0 FIELD TESTING OF MODULES, DATA ACQUISITION AND ANALYSIS

8.1 Purpose of Task 9

The goal of this task was to assess performance of experimental encapsulants when used in full size modules deployed in a region of comparatively high temperature and solar irradiance. Specifically, the intent was to determine degree of browning, if any, of encapsulants over time and any associated power loss.

8.2 Testing procedure

In support of this task, ASU installed a two axis tracker at the STAR (Solar Testing and Research) facility, Arizona Public Service, Tempe. A concrete pedestal was poured and the tracker assembly, a refurbished Martin Marietta system, was added. The superstructure, which was designed to hold up to 50 nominal 50 watt modules, was mounted on the torque tube.

Finally, power and control circuits were installed, and the entire system was "debugged" during July and August 1996.

Fresh quantities of experimental encapsulants were extruded at STR in Enfield and shipped to team members.

Team members prepared the same type of modules that were submitted for Task 8 Qual. Testing, with the exception that wherever a glass superstrate was used, it was a cerium oxide-containing glass, either Solarphire, Solite II or Solatex II. Modules/encapsulants requested from each team member are summarized in Table 12. Two members elected to not submit modules at that time, but there will be space on the tracker should they provide modules at some future date.

All modules were shipped to STAR where ASU installed them on the tracker (Figure 19). Each module was connected with a fixed resistive load which allowed it to operate at or near the peak power point. A total of 36 modules were installed by August 29, and initial IV curves were taken on each for baseline electrical performance. Detailed data is provided in Appendix C.

Photos were taken of each module for a permanent visual record. These photos were transferred to diskette for easy referencing and archiving. Conventional negatives were also retained.

Thermal imaging with an IR camera was completed on October 1. Peter Bliven, president of PBA instruments and an expert in thermal imaging, collected and processed the data, with assistance from ASU. Both hard copy (color images) and computer files have been retained. IR image data were taken with the modules at peak power and again short circuited. Some shorted modules exhibited hot spots with one cell reaching 86.6° C; nine other modules had "hot" cells that ranged in temperature from 70.1 to 78.3° C. These same cells with a fixed resistive load operated at about 65° C

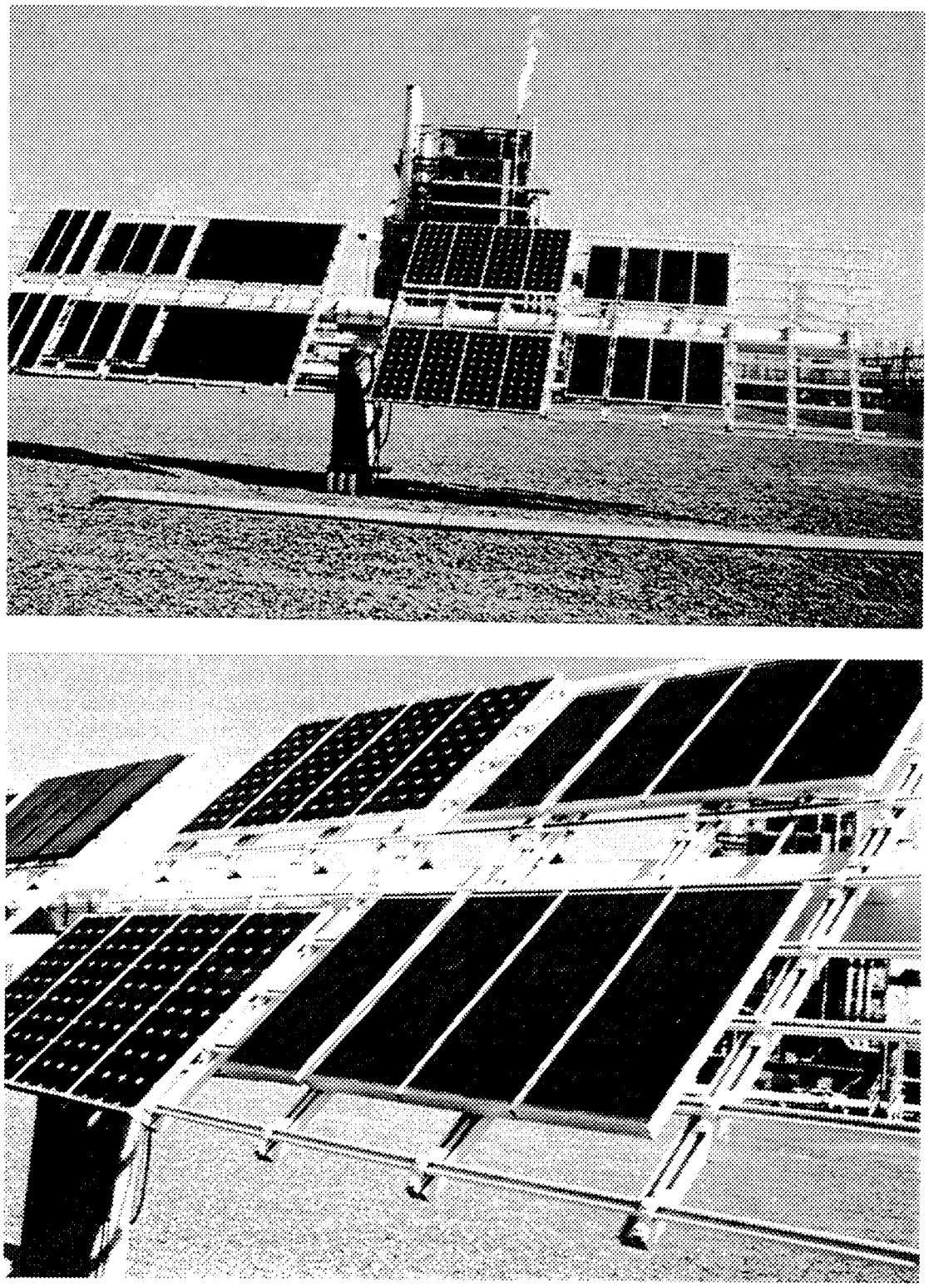

Figure 19 – Modules with Experimental Encapsulants on Two-Axis Tracker at STAR, Tempe, AZ

9.0 CONCLUSIONS AND RECOMMENDATIONS

Summary and Conclusions

9.1: Phase I - Further Problem Definition

This phase comprised a literature search on EVA-based encapsulant browning, a survey of and site visits to installations reporting discolored EVA-based encapsulant in fielded modules, and analysis of browned EVA-based encapsulant. The purpose was to better understand the parameters influencing browning and the probable chemical mechanisms involved in this color development. Conclusions are:

Survey

9.1.1: The incidence of EVA-based encapsulant browning is not limited to the modules of any one particular manufacturer. Browned modules from several suppliers were observed.

9.1.2: The incidence of EVA-based encapsulant browning is not limited to the encapsulant sheet provided by any one supplier.

9.1.3: Visually, the rate of browning appears to be module manufacturer dependent. There is one module manufacturer whose modules consistently discolor less rapidly than any others that have been tested in the field in excess of four years.

9.1.4: The incidence of EVA-based encapsulant browning appears to be primarily in the West and Southwest where there is comparatively high solar insolation and higher operating temperatures.

9.1.5: EVA-based encapsulant browning appears to be more intense at test facilities that have a combination of high module operating temperature and high solar insolation.

Laboratory Aging Studies

9.1.6: Accelerated aging studies suggest that encapsulant browning is not related to the EVA base resin alone; without additives there is no discoloration. In particular, for one series of tests a "standard cure" A9918P encapsulant laminated between low iron glass showed significant yellowing after 17 weeks in a Xenon Arc Weather-O-Meter, while "neat" EVA resin, Elvax 3185 with no additives, showed little or no yellowing after the same exposure.

9.1.7: These studies also suggest that photochemistry of encapsulant browning is related to specific additives in the formulation, in particular Naugard P and an interaction between Lupersol 101 and Cyasorb UV-531. What is not known at this point is if the reaction products of Naugard P and Cyasorb UV-531 with Lupersol are in turn involving the EVA polymer in some way.

During a comparable series of aging studies, when one additive at a time was systematically removed from A9918P, discoloration was greatly reduced. And when only one additive at a time was used in Elvax 3185, discoloration was significantly diminished or eliminated.

9.1.8: When "fast cure" 15295P was substituted for A9918P in some accelerated aging samples, the rate of yellowing was reduced by a factor of approximately 2.5 after 17 weeks in the Weather-O-Meter. The reduced yellowing appears to be a result of a different chemical composition for the peroxide crosslinker in 15295P, Lupersol TBEC rather than Lupersol 101, the only difference between the two types of encapsulant.

Instrumental Analysis

9.1.9: Various analyses on browned and unaged EVA-based encapsulant support and corroborate the findings of the laboratory aging studies (items 9.1.6 through 9.1.8 above). Specifically, analytical investigations show no evidence of conjugated unsaturation in the EVA polymer, which tends to discount polyene chromophores as the mechanism for encapsulant browning. However, the analyses support an interaction of additives as a cause of yellowing.

9.1.10: Infrared spectroscopy does not indicate the presence of significant amounts of unsaturation in discolored EVA-based encapsulant. IR spectra of unaged and highly discolored encapsulants were practically superimposable with no perceptible absorption in the region of the spectra where double bonds would have been expected to have absorbed.

9.1.11: Controlled oxidation of browned encapsulant discounts the presence of conjugated unsaturation or polyenes. When treated with peracetic acid, browned encapsulant did not lose its color. A PVC control, which had purposely been degraded to create conjugated unsaturation and a dark brown color, was bleached to a translucent white when its was treated in a like manner with peracetic acid.

9.1.12: Raman spectroscopy showed that discolored, field-aged encapsulant lacked evidence of unsaturation, which was clearly shown for the discolored PVC sample (section 9.1.11) by a strong band at 1650 cm^{-1}. Also, when the 257 nm beam of the spectrometer was focused on the EVA-based encapsulant for an extended time, unsaturation did develop, indicating that it would have been detected, had it been present initially. If there is no unsaturation, then there are obviously no polyenes.[88]

9.1.13: Neither thermogravimetric analysis (TGA) nor x-ray photoelectron spectroscopy (XPS) show a reduction in vinyl acetate content in browned versus unaged EVA-based encapsulant. Consequently, there appears to be little double bond formation from photolysis of vinyl acetate. And if there is little basis for double bond formation at any level, there is even less reason to expect conjugated double bond sequences of eight or more as would be required to develop color in the EVA.

9.1.14: Residual unreacted Lupersol 101 peroxide remaining after curing of A9918P significantly reduces the concentrations of stabilizing additives based on GC/FID and GC/MS.

Specifically:

Cyasorb UV 531 concentrations suffered little reduction in concentration when a glass/encapsulant/glass laminate of A9918P without Lupersol 101 was exposed in the Weather-O-Meter for ten weeks. On the other hand, samples with the usual amount of Lupersol 101 exhibited a 40% drop in cyasorb UV-531 concentration during 12 weeks Weather-O-Meter exposure. And consistent with aging studies (9.1.6 to 9.1.8) the later showed significant yellowing while the former did not.

The concentration of Tinuvin 770 behaved similarly showing 61% reduction during 12 weeks Weather-O-Meter exposure.

9.1.15: It is likely that transformation products of BHT (butylated hydroxytoluene, in the EVA resin as received from DuPont), Cyasorb UV 531, and nonyl phenol (from reactions of Naugard P), arising from reactions with alkoxy radicals from the photolysis of Lupersol 101, are playing an important role in the discoloration of EVA-based encapsulant. As indicated before, Weather-O-Meter aging studies showed a strong correlation between color development and stabilizing additives/Lupersol 101 interactions (9.1.6, 9.1.7, 9.1.8, and 9.1.14).

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[88] Ezrin, M. et. al., "Further Studies of Discoloration of EVA Encapsulant in Photovoltaic Modules", Proceeding of the SPE Annual Technical Conference, May 1996, Indianapolis.

9.1.16: IR evidence indicates light colored encapsulant areas of modules recovered from the field have experienced oxidation. This suggests the backing is permeable to oxygen which diffuses into the rear of the modules and migrates through regions where there are no silicon cell barriers. Regions reached by oxygen appear to be "photo-oxidatively bleached." Colorless regions in the vicinity of cracks in the cells exhibit this same phenomenon, that is, the crack provides oxygen access to the discolored EVA-based encapsulant above the cells.

9.2 Phase II - Development of Stabilization Strategies

Development work, including reformulation of the EVA-based encapsulants, has revealed:

9.2.1: Four experimental encapsulants greatly reduce browning. After 40 weeks in the Weather-O-Meter, glass/glass laminates prepared with X9903P, X9923P, X9933P and 15303P showed no visible yellowing. Yellowness index was reduced by 10 to 20 versus A9918P. Control laminates with A9918P and 15295P exposed at the same conditions were a dark brown.

And after 40 weeks of accelerated outdoor EMMA exposure in Phoenix at a nominal 5 U.V. suns, glass/glass laminates prepared with X9903P show no measurable yellowing.

9.2.2 The use of cerium oxide-containing glass, Solarphire or Solite or Solatex II, greatly reduces the rate of discoloration of EVA-based A9918P and 15295P, presumably by filtering out much of the UV-B radiation (i.e., 280 to 340 nm). Thirty weeks exposure in the Weather-O-Meter of glass/15295P/glass samples with cerium-oxide containing glass produced a Yellowness Index of 5.2, undetectable by eye, and one year exposure gave a 13 Index. By contrast, after 30 weeks exposure a 15295P control prepared with Starphire low-iron glass had a Yellowness Index of 65 and a dark brown color.

After 18 months of accelerated outdoor EMMA exposure at a nominal 5 U.V. suns, 15295P laminates prepared with cerium-containing glass had no visible color while similar samples using A9918P had almost no visible color. Versus controls, Yellowness Index was reduced by a factor of approximately 15.

9.2.3: When samples of A9918P were evaluated with Tefzel as the superstrate, there was no discoloration during long term accelerated aging by either Weather-O-Meter or by EMMA. Presumably sufficient oxygen gets through the Tefzel to photobleach any chromophores or perhaps to inhibit their formation.

9.2.4: For maximum U.V. and color stability, STR recommends that the new experimental encapsulants, where possible, be used in conjunction with a cerium oxide containing glass superstrate such as Solarphire, Solatex II, or Solite II.

9.3 Phase III - Full Scale Module Fabrication and Testing

9.3.1: The four experimental EVA-based encapsulants from Phase II were successfully prepared on a pilot scale using production equipment.

9.3.2: Encapsulant sheet of the four experimental formulations was used, without significant problems, by six different module producers to fabricate full-size modules. With only a couple of exceptions, curing of these modules was at a consistently high level, with average gel content greater than 83% versus a typical 80% for current EVA-based materials.

9.3.3: A total of 102 modules prepared with the four experimental encapsulants were subjected to IEEE 1262 qualification testing. Except for yellowing of one experimental formulation, X9933P, there was not a single failure related to the encapsulant material.

9.3.4: During IEEE 1262, modules were subjected to damp heat (85° C/85% R.H.), thermal cycling, U.V., etc. Despite these exposures there appeared to be little or no loss of adhesion to cells, interconnects or glass. However,

on a qualitative basis, some backing film laminates showed a loss of adhesion to the encapsulant as a result of damp heat. These backings also developed a brown discoloration which was traced to the adhesive/tie layer.

9.3.5: A total of 36 modules, representing four different experimental encapsulants and six separate manufacturers were deployed on a two-axis tracker at the STAR facility of Arizona Public Service in Tempe. Another 12 control modules, prepared with A9918P, are in the process of being installed.

9.3.6: An expanded family of encapsulants is now commercially available in sheet form from STR for use by module manufacturers for a variety of constructions and applications. However, it is essential that module makers perform their own evaluation of these encapsulants in their module design(s) of interest.

Recommendations for Further Work

9.4: While accelerated weathering testing can be helpful in discriminating between various encapsulant systems, ultimately the only reliable lifetime evaluation is long term field testing of modules under simulated end use conditions. During this program nearly 50 modules, representing four experimental encapsulants and six different stabilization strategies, were installed on a two axis tracker at STAR in Tempe, Arizona. These modules have been on test for a year.

STR intends to continue this testing indefinitely - for at least 20 years or until there are conclusive results on the long term performance of these modules. Interim results will be reported at upcoming industry conferences.

9.5: The test modules have been placed in an area of the country where the temperature and solar insolation are comparatively high - a condition which is known to accelerate browning in conventional A9918P EVA-based encapsulant. Of course, this is a comparatively dry environment.

Given the adverse effect that moisture can have on PV modules, it would provide important information if a set of modules, similar to those at STAR, were fielded in a region of comparatively high solar insolation and temperature and high humidity as well. One possible location would be FSEC in Cape Canaveral, Florida.

9.6: During this PVMaT program, the mechanism for browning of A9918P was examined only in enough detail to provide a working hypothesis from which stabilization strategies could be developed. There are still some unanswered questions on the interaction of additives in A9918P. Some more basic research is needed to separate, isolate, and characterize those transformation products which give rise to the brown color.

9.7: Finally, it will be important to evaluate these new encapsulant systems in a broader range of module types and under a variety of environmental conditions. Here we hope that the individual module manufacturers will conduct their own investigations of these encapsulants.

Appendix A

Team Members

Company	Contact	Location
Astropower	Pat Lasswell	Newark, DE
EBARA Solar, Inc.	Richard Rosey	Large, PA
Photocomm, Inc.	Steve Allan	Scottsdale, AZ
Solarex Corp.	John Wohlgemuth	Frederick, MD
Siemens Solar Industries	Theresa Jester & Jean Hummel	Camarillo, CA
ASE Americas, Inc.	Juris Kalejs & Ron Gonsiorawski	Billerica, MA
Solec International, Inc.	Ishaq Shahryar & Dave Tanner	Hawthorne, CA
United Solar Systems Corp.	Subhendu Guha	Troy, MI
ASU, Photovoltaic Testing Laboratory:	Bob Hammond & Kent Whitfield	Tempe, AZ
UCONN, Institute for Materials Science	Meyer Ezrin & Peter Klemchuk	Storrs, CT

APPENDIX B

Springborn Qual Test (IEEE 1262, Modified)

Summary of Abnormal Test Results

Manufacturer: A					
Module S/N	**Date**	**Seq.**	**Test Condition**	**Pass /Fail**	**Results and Comments**
Encapsulant: x9903p					
38	7/29/96	5.1.1	Initial visual inspection	P	Very small lines (possible delamination) near cell surface
48	7/31/96	5.2	Pre-Seq. elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (88%)
52	8/26/96	5.13	Damp heat (85/85)	NA	Exposed 495hrs instead of 1000hrs due to late shipping
52	8/26/96	5.1.2	Damp heat (85/85) visual	P	J-box distorted
55	n/a	5.17	UV	NA	Did not test due to late shipping
55	8/30/96	5.1.2	TC50 visual	P	J-box distorted
55	10/4/96	5.1.2	HF10 visual	P	J-box distorted
56	n/a	5.17	UV	NA	Did not test due to late shipping
56	10/4/96	5.1.2	HF10 visual	P	Slight encapsulant yellowing, J-box distorted
61	8/26/96	5.13	Damp heat (85/85)	NA	Exposed 495hrs instead of 1000hrs due to late shipping
61	8/26/96	5.1.2	Damp heat (85/85) visual	P	Edge delamination, 22"X0.5", J-box distorted
Encapsulant: x9933p					
41	8/26/96	5.13	Damp heat (85/85)	NA	Exposed 495hrs instead of 1000hrs due to late shipping
41	8/26/96	5.1.2	Damp heat (85/85) visual	P	Encapsulant yellow throughout, J-box distorted
42	n/a	5.17	UV	NA	Did not test due to late shipping
42	10/4/96	5.1.2	HF10 visual	P	Encapsulant yellowing, J-box distorted
53	11/18/96	5.1.2	TC 200 visual	P	Encapsulant yellowing at cell edges and along leads
57	11/18/96	5.1.2	TC 200 visual	P	Encapsulant yellowing at cell edges and along leads, J-box distorted, very small lines (possible delamination) near cell surface
59	8/26/96	5.13	Damp heat (85/85)	NA	Exposed 495hrs instead of 1000hrs due to late shipping
59	8/26/96	5.1.2	Damp heat (85/85) visual	P	Encapsulant yellow throughout, J-box distorted
60	n/a	5.17	UV	NA	Did not test due to late shipping
60	10/4/96	5.1.2	HF10 visual	P	Slight encapsulant yellowing, J-box distorted
Encapsulant: x15303p					
45	8/26/96	5.13	Damp heat (85/85)	NA	Exposed 495hrs instead of 1000hrs due to late shipping
45	8/26/96	5.1.2	Damp heat (85/85) visual	P	Edge delamination 5"X0.5", J-box distorted

46	n/a	5.17	UV	NA	Did not test due to late shipping	
46	10/4/96	5.1.2	HF10 visual	P	J-box distorted	
46	8/26/96	5.13	Damp heat (85/85)	NA	Exposed 495hrs instead of 1000hrs due to late shipping	
47	8/26/96	5.1.2	Damp heat (85/85) visual	P	Edge delamination 12"X0.5", J-box distorted	
49	n/a	5.17	UV	NA	Did not test due to late shipping	
49	10/4/96	5.1.2	HF10 visual	P	Slight encapsulant browning, J-box distorted	
58	7/29/96	5.1.1	Initial visual inspection	P	Very small lines (possible delamination) near cell surface	
Note :						
NA		Not Applicable				

Springborn Qual Test (IEEE 1262, Modified)					
Summary of Abnormal Test Results					
Manufacturer: B					
Module S/N	**Date**	**Seq.**	**Test Condition**	**Pass /Fail**	**Results and Comments**
Encapsulant: x9923p					
32	11/18/96	5.1.2	TC 200 visual	P	Square shaped bubbles on substrate
32	11/19/96	5.2	TC 200 elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (87%)
32	11/25/96	5.2	Final elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (88%)
36	6/28/96	5.1.1	Baseline visual	P	Scratches on substrate
36	11/18/96	5.1.2	TC 200 visual	P	Square shaped bubbles on substrate
36	11/19/96	5.2	TC 200 elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (81%)
36	11/25/96	5.2	Final elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (88%)
37	8/30/96	5.1.2	TC50 visual	P	Bubbles in encapsulant
37	9/9/96	5.2	TC50 elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (82%)
37	11/19/96	5.2	HF10 elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (87%)
35	8/30/96	5.1.2	TC50 visual	P	Bubbles in encapsulant
35	9/9/96	5.2	TC50 elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (85%)
33	8/26/96	5.1.2	Damp heat (85/85) visual	P	Slight encapsulant yellowing at mfg's front label
33	11/25/96	5.2	Final elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (89%)
76	8/26/96	5.1.2	Damp heat (85/85) visual	P	Very slight encap. yellowing at mfg's front label
76	11/25/96	5.2	Final elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (87%)
Encapsulant: x9933p					
41	6/28/96	5.1.1	Baseline visual	P	Bubbles in encapsulant
41	11/18/96	5.1.2	TC 200 visual	P	Slight encapsulant yellowing around bus and cell edges
39	6/28/96	5.1.1	Baseline visual	P	Bubbles in encapsulant
39	6/28/96	5.1.2	TC 200 visual	P	Slight encapsulant yellowing, bubbles in encapsulant
40	8/30/96	5.1.2	TC50 visual	P	Bubbles in encapsulant
40	10/4/96	5.1.2	HF10 visual	P	Slight encapsulant yellowing
45	8/30/96	5.1.2	TC50 visual	P	Bubbles in encapsulant
45	10/4/96	5.1.2	HF10 visual	P	Slight encapsulant yellowing
44	8/26/96	5.1.2	Damp heat (85/85) visual	P	Encapsulant yellow, possible delamination
38	8/26/96	5.1.2	Damp heat (85/85) visual	P	Encapsulant yellow, possible delamination

Encapsulant: x15303p					
41	6/28/96	5.1.1	Baseline visual	P	Bubbles between superstrate and cells
41	11/18/96	5.1.2	TC 200 visual	P	Large number of small bubbles between superstrate and cells
44	6/28/96	5.1.1	Baseline visual	P	Bubbles between superstrate and cells
44	8/30/96	5.1.2	TC50 visual	P	Bubbles and indentations on substrate
40	6/28/96	5.1.1	Baseline visual	P	Bubbles between superstrate and cells
45	6/28/96	5.1.1	Baseline visual	P	Bubbles between superstrate and cells

Springborn Qual Test (IEEE 1262, Modified)					
Summary of Abnormal Test Results					
Manufacturer: C					
Module S/N	**Date**	**Seq.**	**Test Condition**	**Pass /Fail**	**Results and Comments**
Encapsulant: x9903p					
36	6/27/96	5.1.1	Baseline visual	P	Bubbles in encapsulant
36	11/18/96	5.1.2	TC 200 visual	P	Bubbles in encapsulant, spiders on some cell backs
32	6/27/96	5.1.1	Baseline visual	P	Cracked cell
32	11/18/96	5.1.2	TC 200 visual	P	Four cracked cells, bubbles in encapsulant
35	10/4/96	5.1.2	HF10 visual	P	Terminal corrosion
33	6/27/96	5.1.1	Baseline visual	P	Bubbles in encapsulant, scratches on superstrate
33	10/4/96	5.1.2	HF10 visual	P	Terminal corrosion
34	6/27/96	5.1.1	Baseline visual	P	1" long crack on a cell
34	8/26/96	5.1.2	Damp heat (85/85) visual	P	Terminal corrosion
31	6/27/96	5.1.1	Baseline visual	P	Terminal corrosion
31	8/26/96	5.1.2	Damp heat (85/85) visual	P	Terminal corrosion
Encapsulant: x9923p					
36	6/27/96	5.1.1	Baseline visual	P	Bubbles in encapsulant
36	11/18/96	5.1.2	TC 200 visual	P	Bubbles in encapsulant, spiders on some cell backs
34	6/27/96	5.1.1	Baseline visual	P	Bubbles in encapsulant
34	11/18/96	5.1.2	TC 200 visual	P	Three cracked cells, bubbles in encap., spiders on some cell backs
10	6/27/96	5.1.1	Baseline visual	P	Bubbles in encapsulant
10	10/4/96	5.1.2	HF10 visual	P	Terminal corrosion
13	10/4/96	5.1.2	HF10 visual	P	Terminal corrosion
33	8/26/96	5.1.2	Damp heat (85/85) visual	P	Metalization (ribbon) discolored above J-box, white corrosion on terminals
31	8/26/96	5.1.2	Damp heat (85/85) visual	P	Metalization (ribbon) discolored above J-box, white corrosion on terminals
31	6/27/96	5.1.1	Baseline visual	P	Bubbles in encapsulant
Encapsulant: x9933p					

35	11/18/96	5.1.2	TC 200 visual	P	Spiders on some cell backs
31	6/27/96	5.1.1	Baseline visual	P	Cracked cell
31	11/18/96	5.1.2	TC 200 visual	P	Spiders on some cell backs, one cracked cell
33	6/27/96	5.1.1	Baseline visual	P	Bubbles in encapsulant
33	10/4/96	5.1.2	HF10 visual	P	Terminal corrosion
32	10/4/96	5.1.2	HF10 visual	P	Terminal corrosion
36	8/26/96	5.1.2	Damp heat (85/85) visual	P	Encapsulant yellow throughout, terminal corrosion
34	8/26/96	5.1.2	Damp heat (85/85) visual	P	Encapsulant yellow throughout, terminal corrosion

Springborn Qual Test (IEEE 1262, Modified)					
Summary of Abnormal Test Results					
Manufacturer: D					
Module S/N	**Date**	**Seq.**	**Test Condition**	**Pass /Fail**	**Results and Comments**
Encapsulant: x9903p					
1	11/18/96	5.1.2	TC 200 visual	P	Delamination (1"x2"), laminate shrinkage between cells
8	6/28/96	5.6	Initial wet hi-pot	F	Short circuit between leads and frame
8	11/18/96	5.1.2	TC 200 visual	P	Delam. (1"x1 1/2"), laminate shrinkage between cells
8	11/22/96	5.5	Final wet insulation	F	Arc
8	11/22/96	5.6	Final wet hi-pot	F	Arc
11	8/30/96	5.1.2	TC50 visual	P	Lam. shrinkage between cells, encap. yellow along leads
11	10/4/96	5.4	HF10 dry hi-pot	F	Arc
11	10/4/96	5.1.2	HF10 visual	P	Lead corrosion near J-box, delamination around cell edges
11	10/4/96	5.5	Final wet insulation	F	High leakage current
11	10/4/96	5.6	Final wet hi-pot	F	High leakage current
10	8/30/96	5.1.2	TC50 visual	P	Lam. shrinkage between cells, encap. yellow along leads
10	10/4/96	5.4	HF10 dry hi-pot	F	Arc
10	10/4/96	5.1.2	HF10 visual	P	Lead corrosion near J-box, delamination around cell edges
16	6/28/96	5.1.1	Baseline visual	P	Two cells touching
16	8/26/96	5.1.2	Damp heat (85/85) visual	P	Slight encapsulant browning, J-box distorted, 30 in^2 delam
13	8/26/96	5.1.2	Damp heat (85/85) visual	P	Slight encap. browning, J-box distorted, 30 in^2 delam, ribbon corrosion
Encapsulant: x9923p					
7	11/18/96	5.1.2	TC 200 visual	P	Laminate shrinkage between cells
19	6/28/96	5.1.1	Baseline visual	P	Bubbles in encapsulant
19	11/18/96	5.1.2	TC 200 visual	P	Several small delaminations (0.25"x0.25"), lam. shrinkage
6	8/30/96	5.1.2	TC50 visual	P	Lam. shrinkage between cells, encap. yellow along leads
6	10/4/96	5.4	HF10 dry hi-pot	F	Arc
6	10/4/96	5.1.2	HF10 visual	P	Loose bond between frame and module
24	8/30/96	5.1.2	TC50 visual	P	Lam. shrinkage between cells, encap. yellow along leads
24	10/4/96	5.4	HF10 dry hi-pot	F	Arc

12	8/26/96	5.4	Damp heat (85/85) dry hi-pot	F	Arc
12	8/26/96	5.1.2	Damp heat (85/85) visual	P	Some encap. browning, J-box distorted, 80 in^2 delam.
12	9/12/96	5.2	Damp heat (85/85) elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (84%)
5	8/26/96	5.1.2	Damp heat (85/85) visual	P	Slight encap. browning, J-box distorted, 45 in^2 delam., ribbon corrosion
Encapsulant: x9933p					
4	11/18/96	5.1.2	TC 200 visual	P	lam. shrinkage between cells, encap. yellow throughout
18	6/28/96	5.6	Initial wet hi-pot	F	Short circuit between leads and frame
18	11/18/96	5.1.2	TC 200 visual	P	Delam. (1/4"x1 1/2"), laminate shrinkage between cells, slight encapsulant yellowing
18	11/22/96	5.5	Final wet insulation	F	Arc
18	11/22/96	5.6	Final wet hi-pot	F	Arc
9	8/30/96	5.1.2	TC50 visual	P	Lam. shrinkage between cells, encap. yellow throughout
9	10/4/96	5.4	HF10 dry hi-pot	F	Arc
9	10/4/96	5.1.2	HF10 visual	P	Encapsulant yellow throughout
9	11/19/96	5.2	HF10 elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (89%)
9	11/21/96	5.4	Final dry hi-pot	F	Arc
9	11/21/96	5.5	Final wet insulation	F	High leakage current
3	8/30/96	5.1.2	TC50 visual	P	Superstrate torn-2" long, lamin. shrinkage between cells, encap. yellow throughout, two cells discolored
3	10/4/96	5.4	HF10 dry hi-pot	F	Arc
3	10/4/96	5.1.2	HF10 visual	P	Encapsulant yellow throughout, superstrate torn
3	11/19/96	5.2	HF10 elec. perf. (I-V)	?	Max. power less than 90% of the baseline power (87%)
3	11/22/96	5.5	Final wet insulation	F	High leakage current
3	11/22/96	5.6	Final wet hi-pot	F	High leakage current
17	8/26/96	5.4	Damp heat (85/85) dry hi-pot	F	Arc
17	8/26/96	5.1.2	Damp heat (85/85) visual	P	Encapsulant yellow throughout, J-box distorted, 20 in^2 delamination
17	11/22/96	5.5	Final wet insulation	F	High leakage current
17	11/22/96	5.6	Final wet hi-pot	F	High leakage current
15	11/22/96	5.5	Final wet insulation	F	High leakage current
15	11/22/96	5.6	Final wet hi-pot	F	High leakage current
Encapsulant: x15303p					
20	6/28/96	5.1.1	Baseline visual	P	Two cells touching

20	11/18/96	5.1.2	TC200 visual	P	Laminate shrinkage between cells
21	11/18/96	5.1.2	TC200 visual	P	Laminate shrinkage between cells
22	8/30/96	5.1.2	TC50 visual	P	Lam. shrinkage between cells, encap. yellow along leads
22	10/4/96	5.4	HF10 dry hi-pot	F	Arc
25	8/30/96	5.1.2	TC50 visual	P	Lam. shrinkage between cells, encap. yellow along leads
25	10/4/96	5.4	HF10 dry hi-pot	F	Arc
25	11/21/96	5.4	Final dry hi-pot	F	Arc
26	6/28/96	5.6	Initial wet hi-pot	F	Short circuit between leads and frame
26	8/26/96	5.1.2	Damp heat (85/85) visual	P	Some encapsulant browning, J-box distorted, 24 in^2 delam
26	11/22/96	5.5	Final wet insulation	F	High leakage current
26	11/22/96	5.6	Final wet hi-pot	F	High leakage current
23	8/26/96	5.4	Damp heat (85/85) dry hi-pot	F	Arc
23	8/26/96	5.1.2	Damp heat (85/85) visual	P	Some browning, J-box distorted
Note :					
	Because of construction, these modules cannot be field insulated (e.g., Tefzel taped) in the event of a short.				

Springborn Qual Test (IEEE 1262, Modified)					
Summary of Abnormal Test Results					
Manufacturer: E					
Module S/N	**Date**	**Seq.**	**Test Condition**	**Pass /Fail**	**Results and Comments**
Encapsulant: x15303p					
18	6/28/96	5.1.1	Baseline visual	P	Frame bent (superficial)
18	6/29/96	5.5	Initial wet insulation-resistance	P	Short due to pinhole on substrate, repair with TEFZEL film-pass on re-test
18	6/29/96	5.6	Initial wet hi-pot	P	Short due to pinhole on substrate, repair with TEFZEL film-pass on re-test
18	11/26/96	5.5 & 5.6	Final wet-insulation & wet hi-pot	P	Short due to pinhole on substrate, repair with TEFZEL film-pass on re-test
16	6/29/96	5.5	Initial wet insulation-resistance	P	Short due to pinhole on substrate, repair with TEFZEL film-pass on re-test
16	6/29/96	5.6	Initial wet hi-pot	P	Short due to pinhole on substrate, repair with TEFZEL film-pass on re-test
16	8/26/96	5.1.2	Damp heat (85/85) visual	P	Slight encapsulant browning near J-box ribbon
15	8/26/96	5.1.2	Damp heat (85/85) visual	P	Slight encapsulant browning near J-box ribbon

Springborn Qual Test (IEEE 1262, Modified)					
Summary of Abnormal Test Results					
Manufacturer: F					
Module S/N	**Date**	**Seq.**	**Test Condition**	**Pass /Fail**	**Results and Comments**
Encapsulant: x9903p					
76	6/28/96	5.5	Initial wet insulation resistance	F	Short circuit between leads and frame
76	6/28/96	5.6	Initial wet hi-pot	F	Short circuit between leads and frame
76	12/18/96	5.5&5.6	wet insul.&wet hi-pot	P	Repaired pin holes with Tefzel tape
79	10/4/96	5.1.2	HF10 visual	P	Slight encapsulant browning, terminals heavily corroded
80	6/27/96	5.1.1	Baseline visual	P	Scratch on substrate, 1/2" long
80	10/4/96	5.1.2	HF10 visual	P	Slight encapsulant browning, terminals heavily corroded
81	8/26/96	5.1.2	Damp heat (85/85) visual	P	Slight encapsulant browning, terminals heavily corroded
81	6/28/96	5.3	Initial ground continuity	F	Two corner joints non-conductive
81	8/26/96	5.1.2	Damp heat (85/85) visual	P	Slight encapsulant browning, terminals heavily corroded
81	12/5/96	5.3	Final ground continuity	F	Two corner joints non-conductive
Encapsulant: x9933p					
72	11/18/96	5.1.2	TC 200 visual	P	Encap. yellowing around bus, corner frame separation ~2mm
73	11/18/96	5.1.2	TC 200 visual	P	Slight encapsulant yellowing around bus
71	6/28/96	5.5	Initial wet insulation resistance	F	Arc
71	6/28/96	5.6	Initial wet hi-pot	F	Short circuit between leads and frame
71	8/30/96	5.1.2	TC 50 visual	P	Encapsulant yellow along lead paths
71	12/18/96	5.5&5.6	wet insul.&wet hi-pot	P	Repaired pin holes with Tefzel tape
71	10/4/96	5.1.2	HF10 visual	P	Encapsulant yellow throughout, terminals heavily corroded
75	8/30/96	5.1.2	TC50 visual	P	Encapsulant yellow along lead paths
70	8/26/96	5.1.2	Damp heat (85/85) visual	P	Encapsulant yellow throughout, terminals corroded
74	8/26/96	5.1.2	Damp heat (85/85) visual	P	Encapsulant yellow throughout, terminals corroded
Encapsulant: x15303p					
3	6/28/96	5.3	Initial ground continuity	F	Two corner joints non-conductive
3	12/5/96	5.3	Final ground continuity	F	Two corner joints non-conductive
4	8/30/96	5.1.2	TC50 visual	P	Slight discoloration on substrate
4	10/4/96	5.1.2	HF10 visual	P	Slight encapsulant browning, terminals heavily corroded

6	6/28/96	5.3	Initial ground continuity	F	Two corner joints non-conductive
6	10/4/96	5.1.2	HF10 visual	P	Slight encapsulant browning, terminals heavily corroded
6	12/5/96	5.3	Final ground continuity	F	Two corner joints non-conductive
5	8/26/96	5.1.2	Damp heat (85/85) visual	P	Slight encapsulant browning, terminals corroded
69	6/28/96	5.3	Initial ground continuity	F	Two corner joints non-conductive
69	6/28/96	5.5	Initial wet insulation resistance	F	Arc
69	6/28/96	5.6	Initial wet hi-pot	F	Short circuit between leads and frame
69	8/26/96	5.1.2	Damp heat (85/85) visual	P	Slight encapsulant browning, terminals corroded
69	12/18/96	5.5&5.6	wet insul.&wet hi-pot	P	Repaired pin holes with Tefzel tape
69	12/5/96	5.3	Final ground continuity	P	Grounding path apparantly established during testing
Note :					
	Because of the construction method used on these modules, a ground continuity path cannot be created after manufacturing.				

Springborn Qual Test: Outdoor Exposure @ STAR Center

Electrical Performance Test Results

Manufacturer: B

ACTUAL					STC						
Date	**Time**	**Ref. Cell**	**Irrad. W/m^2**	**Temp. (C)**	**Voc (V)**	**Isc (A)**	**Vmax (V)**	**Imax (A)**	**FF (%)**	**Pmax (W)**	**Power % Δ**
Encapsulant: x15303p					**S/N: 20**			**Location:**	**01**		
9/6/96	14:34	SSI002	1021.7	61.4	21.81	3.33	17.53	3.00	72.33	52.53	100.0
10/10/96	13:30	SSI001	1029.4	66.7	21.68	3.30	17.15	2.99	71.60	51.29	97.6
12/5/96	10:02	SSI002	999.9	43.0	21.73	3.36	16.87	3.07	70.98	51.86	98.7
3/27/97	9:37	SSI002	962.7	46.8	21.79	3.38	17.31	3.05	71.56	52.74	100.4
Encapsulant: x15303p					**S/N: 19**			**Location:**	**02**		
9/6/96	14:24	SSI002	1032.9	58.0	21.56	3.32	17.23	3.01	72.49	51.88	100.0
10/10/96	13:37	SSI001	1027.9	60.5	21.53	3.24	16.80	3.02	72.77	50.81	97.9
12/5/96	10:04	SSI002	999.5	40.3	21.88	3.31	17.26	3.04	72.60	52.55	101.3
3/27/97	9:41	SSI002	950.7	36.6	21.26	3.31	16.78	3.03	72.16	50.84	98.0
Encapsulant: x9933p					**S/N: 15**			**Location:**	**03**		
9/6/96	14:16	SSI002	1037.6	58.6	21.73	3.28	17.17	3.02	72.67	51.84	100.0
10/10/96	13:44	SSI001	1033.9	63.4	21.75	3.21	17.26	2.95	72.88	50.89	98.2
12/5/96	10:06	SSI002	1002.8	36.9	21.60	3.29	16.98	3.01	72.04	51.19	98.8
3/27/97	9:54	SSI002	997.6	45.3	21.73	3.28	17.39	2.97	72.51	51.70	99.7
Encapsulant: x9933p					**S/N: 16**			**Location:**	**04**		
9/6/96	14:30	SSI002	1021.5	58.5	21.59	3.29	17.32	2.98	72.75	51.69	100.0
10/10/96	14:00	SSI001	1023.4	73.5	22.16	3.20	17.90	2.95	74.34	52.78	102.1
12/5/96	10:10	SSI002	1004.9	44.2	22.02	3.28	17.37	3.00	72.00	52.03	100.7
3/27/97	10:04	SSI002	1013.3	33.7	21.70	3.29	17.35	2.98	72.37	51.63	99.9
Encapsulant: x9923p					**S/N: 18**			**Location:**	**05**		
9/6/96	14:26	SSI002	1036.4	55.0	21.46	3.37	15.77	2.90	63.18	45.66	100.0
10/10/96	14:05	SSI001	1009.8	69.6	21.99	3.33	16.83	2.76	63.59	46.50	101.8
12/5/96	10:12	SSI002	1005.2	39.0	21.79	3.36	15.47	2.94	62.12	45.42	99.5
3/27/97	10:13	SSI002	956.5	46.2	21.79	3.37	15.84	2.90	62.66	45.94	100.6
Encapsulant: x9923p					**S/N: 17**			**Location:**	**06**		
9/6/96	14:19	SSI002	1030.6	56.7	21.37	3.35	15.32	2.81	60.06	42.99	100.0
10/10/96	14:13	SSI001	1013.8	67.6	21.84	3.30	15.85	2.79	61.55	44.30	103.0
12/5/96	10:15	SSI002	1007.0	38.2	21.58	3.30	15.16	2.80	59.63	42.47	98.8
3/27/97	9:58	SSI002	891.5	42.9	21.42	3.31	15.75	2.74	60.91	43.21	100.5

Springborn Qual Test: Outdoor Exposure @ STAR Center											
Electrical Performance Test Results											
	Manufacturer: C										
ACTUAL					**STC**						
Date	**Time**	**Ref. Cell**	**Irrad. W/m^2**	**Temp. (C)**	**Voc (V)**	**Isc (A)**	**Vmax (V)**	**Imax (A)**	**FF (%)**	**Pmax (W)**	**Power % D**
Encapsulant: x9933p					**S/N: 38**			**Location:**	**07**		
9/6/96	13:17	ASEA2679	1007.3	57.1	20.70	3.52	16.79	2.66	61.37	44.73	100.0
10/10/96	14:43	ASEA2679	1004.3	69.6	21.05	3.54	17.25	2.55	58.84	43.90	98.1
12/5/96	10:30	ASEA2673	1005.1	40.2	20.49	3.25	16.10	2.72	65.82	43.78	97.9
3/27/97	10:19	SSI002	999.9	43.2	20.54	3.24	16.57	2.64	65.62	43.69	97.7
Encapsulant: x15295p					**S/N: 51**			**Location:**	**08**		
9/6/96	13:11	ASEA2679	991.2	60.4	20.83	3.53	16.65	2.71	61.45	45.14	100.0
10/10/96	14:52	ASEA2679	990.3	68.3	21.22	3.48	17.40	2.56	60.23	44.51	98.6
12/5/96	10:33	ASEA2673	1003.0	31.5	20.08	3.14	15.60	2.75	68.21	42.95	95.1
3/27/97	10:22	SSI002	1002.8	38.5	20.38	3.17	16.21	2.68	67.18	43.39	96.1
Encapsulant: x9933p					**S/N: 37**			**Location:**	**09**		
9/6/96	13:05	ASEA2679	1002.2	59.8	20.97	3.51	16.81	2.71	61.90	45.51	100.0
10/10/96	14:57	ASEA2679	972.8	65.8	21.16	3.41	16.95	2.62	61.52	44.38	97.5
12/5/96	10:36	ASEA2673	990.3	39.0	20.73	3.16	16.53	2.70	68.01	44.58	98.0
3/27/97	10:24	SSI002	990.7	46.7	20.98	3.22	16.84	2.67	66.42	44.89	98.6
Encapsulant: x9903p					**S/N: 37**			**Location:**	**10**		
9/6/96	13:31	ASEA2679	1004.6	61.6	20.81	3.56	16.96	2.64	60.43	44.78	100.0
10/10/96	15:23	ASEA2679	956.0	65.3	21.24	3.38	17.36	2.53	61.21	44.00	98.3
12/5/96	10:39	ASEA2673	995.1	41.4	20.72	3.20	16.51	2.65	66.03	43.77	97.7
3/27/97	10:28	SSI002	1076.7	42.8	20.74	3.20	16.74	2.60	65.68	43.57	97.3
Encapsulant: x9903p					**S/N: 38**			**Location:**	**11**		
9/6/96	13:14	ASEA2679	992.1	56.1	20.64	3.49	16.36	2.74	62.24	44.78	100.0
10/10/96	15:27	ASEA2679	950.5	63.6	21.21	3.37	17.33	2.58	62.38	44.64	99.7
12/5/96	10:41	ASEA2673	990.6	33.1	20.38	3.12	16.14	2.71	68.63	43.68	97.5
3/27/97	10:31	SSI002	1072.1	42.1	20.74	3.20	16.78	2.62	66.36	44.04	98.3
Encapsulant: x15295p					**S/N: 52**			**Location:**	**12**		
9/6/96	13:08	ASEA2679	1006.8	52.0	20.47	3.41	16.19	2.76	64.00	44.65	100.0
10/10/96	15:33	ASEA2679	921.9	62.2	21.01	3.35	17.11	2.59	63.11	44.40	99.4
12/5/96	10:44	ASEA2673	987.8	36.2	20.49	3.15	16.40	2.71	68.95	44.44	99.5
3/27/97	10:36	SSI002	1068.6	29.4	20.90	3.01	16.60	2.70	71.19	44.80	100.3

Springborn Qual Test: Outdoor Exposure @ STAR Center

Electrical Performance Test Results

Manufacturer: D

ACTUAL					STC						
Date	Time	Ref. Cell	Irrad. W/m^2	Temp. (C)	Voc (V)	Isc (A)	Vmax (V)	Imax (A)	FF (%)	Pmax (W)	Power % Δ
Encapsulant: x9933p					S/N: 68			Location:	29		
9/6/96	11:54	SSI002	1019.7	61.8	21.45	3.01	17.16	2.79	74.07	47.85	100.0
10/16/96	14:29	PC02	938.3	49.6	21.36	3.09	18.64	2.63	74.14	48.96	102.3
12/5/96	12:42	PC02	1037.6	45.5	20.96	3.09	16.25	2.87	72.07	46.68	97.6
3/27/97	12:46	SSI002	1069.8	51.1	21.04	3.03	16.51	2.78	72.01	45.84	95.8
Encapsulant: x9903p					S/N: 64			Location:	30		
9/6/96	12:07	SSI002	1036.3	63.3	21.35	3.07	17.01	2.80	72.74	47.71	100.0
10/16/96	14:33	PC02	906.8	44.1	20.60	3.07	16.35	2.82	72.66	46.02	96.4
12/5/96	12:45	PC02	1018.4	38.9	20.63	3.14	15.92	2.90	71.31	46.25	96.9
3/27/97	12:49	SSI002	1075.6	47.5	20.80	3.06	16.10	2.82	71.18	45.35	95.1
Encapsulant: x15295p					S/N: 67			Location:	31		
9/6/96	11:40	SSI002	1016.8	64.1	21.24	3.06	16.82	2.81	72.75	47.27	100.0
10/16/96	14:36	PC02	965.3	52.1	21.24	3.10	16.67	2.90	73.47	48.40	102.4
12/5/96	12:48	PC02	1035.0	47.1	20.99	3.13	16.39	2.89	72.10	47.42	100.3
3/27/97	12:52	SSI002	1075.9	54.4	21.11	3.04	16.62	2.78	71.99	46.27	97.9
Encapsulant: x9903p					S/N: 66			Location:	32		
9/6/96	11:35	SSI002	1014.1	66.5	21.58	3.05	17.12	2.83	73.60	48.39	100.0
10/16/96	14:39	PC02	964.0	55.0	21.50	3.11	17.19	2.86	73.36	49.12	101.5
12/5/96	12:51	PC02	982.2	49.7	21.30	3.13	16.76	2.88	72.52	48.31	99.8
3/27/97	12:54	SSI002	1071.5	59.3	21.55	3.04	17.02	2.78	72.11	47.29	97.7
Encapsulant: x15295p					S/N: 70			Location:	33		
9/6/96	11:58	SSI002	1030.9	61.5	21.36	3.04	17.25	2.77	73.59	47.82	100.0
10/16/96	14:43	PC02	968.5	50.2	21.22	3.10	16.77	2.89	73.64	48.51	101.4
12/5/96	12:53	PC02	1033.1	50.4	21.38	3.12	16.89	2.89	73.12	48.74	101.9
3/27/97	12:57	SSI002	1070.5	59.4	21.57	3.04	17.03	2.83	73.53	48.14	100.7
Encapsulant: x9923p					S/N: 72			Location:	34		
9/6/96	11:51	SSI002	1021.6	63.5	21.13	3.04	16.71	2.77	72.00	46.25	100.0
10/16/96	14:46	PC02	959.6	48.7	20.94	3.08	16.45	2.82	72.05	46.43	100.4
12/5/96	12:56	PC02	1022.8	43.3	20.80	3.08	15.87	2.87	71.19	45.61	98.6
3/27/97	13:00	SSI002	1067.5	49.7	20.89	3.01	16.22	2.75	71.00	44.57	96.4
Encapsulant: x9923p					S/N: 73			Location:	35		
9/6/96	11:43	SSI002	1022.8	63.0	21.27	3.07	16.87	2.84	73.36	47.91	100.0
10/16/96	14:48	PC02	958.2	55.5	21.33	3.10	16.94	2.88	73.79	48.86	102.0
12/5/96	12:58	PC02	780.3	53.4	21.24	3.12	17.17	2.91	75.27	49.87	104.1
3/27/97	13:02	SSI002	1061.9	58.0	21.49	3.06	17.02	2.83	73.22	48.14	100.5
Encapsulant: x9933p					S/N: 71			Location:	36		
9/6/96	11:38	SSI002	1012.9	64.0	21.32	3.02	16.93	2.80	73.46	47.34	100.0
10/16/96	14:51	PC02	952.7	54.3	21.30	3.09	17.04	2.83	73.26	48.27	101.9
12/5/96	13:04	PC02	1056.8	57.3	21.73	3.09	16.92	2.88	72.40	48.65	102.8
3/27/97	13:06	SSI002	1048.5	38.3	21.41	3.05	16.81	2.79	71.72	46.83	98.9

Springborn Qual Test: Outdoor Exposure @ STAR Center											
Electrical Performance Test Results											
	Manufacturer: E										
ACTUAL					**STC**						
Date	**Time**	**Ref. Cell**	**Irrad. W/m^2**	**Temp. (C)**	**Voc (V)**	**Isc (A)**	**Vmax (V)**	**Imax (A)**	**FF (%)**	**Pmax (W)**	**Power % D**
Encapsulant: x15303p					**S/N: 60**			**Location:**	**13**		
9/6/96	12:58	SX502	1017.5	65.7	21.68	3.69	16.99	3.35	71.10	56.91	100.0
10/16/96	11:41	SX698	1002.6	55.6	21.57	3.65	16.97	3.32	71.60	56.29	98.9
12/5/96	10:51	SX698	1014.5	44.9	21.54	3.61	16.82	3.28	70.80	55.12	96.9
3/27/97	11:07	SX698	1065.1	55.9	21.81	3.59	17.42	3.23	71.81	56.30	98.9
Encapsulant: x15303p					**S/N: 54**			**Location: 14**			
9/6/96	12:51	SX502	1010.6	65.3	21.55	3.68	16.85	3.33	70.69	56.07	100.0
10/16/96	11:56	SX698	977.7	57.1	21.58	3.65	17.30	3.26	71.53	56.38	100.5
12/5/96	10:56	SX698	1028.2	43.2	21.41	3.61	16.75	3.29	71.22	55.07	98.2
3/27/97	11:12	SX698	1063.6	56.3	21.73	3.58	16.94	3.30	71.93	55.97	99.8
Encapsulant: x15295p					**S/N: 67**			**Location: 15**			
9/6/96	12:42	SX502	1004.1	66.3	21.95	3.69	17.29	3.34	71.34	57.82	100.0
10/16/96	12:10	SX698	1021.9	61.6	21.77	3.68	16.91	3.38	71.32	57.14	98.8
12/5/96	10:59	SX698	1029.6	44.2	21.78	3.62	17.14	3.31	71.82	56.68	98.0
3/27/97	11:16	SX698	1063.9	58.0	22.06	3.61	17.48	3.29	72.12	57.43	99.3
Encapsulant: x15295p					**S/N: 49**			**Location: 16**			
9/6/96	12:33	SX502	1012.8	66.1	21.54	3.71	16.73	3.36	70.29	56.20	100.0
10/16/96	12:20	SX698	1022.5	58.8	21.55	3.67	16.99	3.30	70.91	56.10	99.8
12/5/96	11:01	SX698	1029.0	41.5	21.40	3.64	16.63	3.32	71.02	55.31	98.4
3/27/97	11:21	SX698	1064.6	49.7	21.37	3.63	17.19	3.20	70.99	55.03	97.9
Encapsulant: x15295p					**S/N: 55**			**Location: 17**			
9/6/96	13:00	SX502	1017.0	64.2	21.60	3.72	16.99	3.34	70.62	56.69	100.0
10/16/96	11:36	SX698	1005.4	57.8	21.65	3.68	17.04	3.34	71.38	56.86	100.3
12/5/96	11:04	SX698	1032.2	46.5	21.64	3.62	17.15	3.27	71.53	56.09	98.9
3/27/97	11:27	SX698	1057.0	59.6	21.86	3.60	17.14	3.30	71.87	56.52	99.7
Encapsulant: x15295p					**S/N: 61**			**Location: 18**			
9/6/96	12:53	SX502	1008.3	60.4	21.32	3.72	16.55	3.38	70.61	55.94	100.0
10/16/96	11:51	SX698	983.8	52.3	21.31	3.68	16.74	3.35	71.41	56.04	100.2
12/5/96	11:07	SX698	1026.4	46.9	21.66	3.62	16.94	3.32	71.64	56.18	100.4
3/27/97	11:31	SX698	1059.0	51.8	21.40	3.62	16.82	3.29	71.40	55.24	98.8
Encapsulant: x15303p					**S/N: 48**			**Location: 19**			
9/6/96	12:48	SX502	997.0	64.9	21.72	3.69	17.02	3.34	71.01	56.87	100.0
10/16/96	12:05	SX698	1020.0	63.0	21.63	3.67	17.14	3.29	70.88	56.32	99.0
12/5/96	11:28	SX698	1032.9	49.0	21.84	3.62	16.96	3.33	71.48	56.45	99.3
3/27/97	11:36	SX698	1061.2	56.3	22.01	3.59	17.41	3.27	71.96	56.87	100.0
Encapsulant: x15303p					**S/N: 66**			**Location: 20**			
9/6/96	12:36	SX502	1004.1	62.7	21.43	3.68	16.76	3.33	70.79	55.77	100.0
10/16/96	12:15	SX698	1022.6	59.9	21.55	3.65	17.25	3.25	71.23	56.07	100.5
12/5/96	11:31	SX698	1040.2	47.0	21.68	3.60	17.31	3.24	71.82	56.08	100.5
3/27/97	11:39	SX698	1071.9	37.4	21.62	3.58	17.38	3.21	72.20	55.84	100.1

Springborn Qual Test: Outdoor Exposure @ STAR Center

Electrical Performance Test Results

Manufacturer: F

ACTUAL					STC						
Date	Time	Ref. Cell	Irrad. W/m^2	Temp. (C)	Voc (V)	Isc (A)	Vmax (V)	Imax (A)	FF (%)	Pmax (W)	Power % D
Encapsulant: x15295p					S/N: 11		Location:		21		
9/6/96	11:10	SSI002	1011.8	60.5	21.11	4.16	16.77	3.44	65.76	57.73	100.0
9/6/96	11:04	SSI002	1010.8	60.1	21.17	4.09	16.57	3.43	65.58	56.81	98.4
9/6/96	10:38	SSI002	1020.9	61.5	21.16	4.02	16.47	3.42	66.20	56.35	97.6
9/6/96	10:47	SSI002	1003.9	56.2	20.81	4.11	16.59	3.41	66.17	56.61	98.1
Encapsulant: x15303p					S/N: 12		Location:		22		
9/6/96	11:13	SSI002	1010.1	63.1	20.73	4.04	16.68	3.36	66.96	56.04	100.0
9/6/96	11:00	SSI002	1002.3	61.5	20.93	4.11	16.63	3.47	67.08	57.65	102.9
9/6/96	10:56	SSI002	1004.4	64.3	21.40	4.10	17.07	3.45	67.10	58.88	105.1
9/6/96	10:42	SSI002	1003.5	60.6	21.30	3.97	17.22	3.35	68.20	57.75	103.1
Encapsulant: x9903p					S/N: 08		Location:		23		
10/16/96	13:02	SX698	1015.2	47.4	20.60	4.21	15.95	3.54	64.99	56.38	100.0
10/16/96	13:39	SX698	1000.0	52.6	20.94	4.14	16.58	3.41	65.33	56.61	100.4
10/16/96	13:45	SX698	1000.4	53.6	21.01	4.11	16.67	3.41	65.77	56.76	100.7
10/16/96	13:52	SX698	1000.7	52.7	21.08	4.11	16.70	3.47	66.78	57.89	102.7
Encapsulant: x9933p					S/N: 07		Location:		24		
10/16/96	13:56	SX698	998.4	45.1	20.19	4.01	16.08	3.35	66.50	53.85	100.0
10/16/96	14:00	SX698	983.2	53.6	20.98	4.13	16.76	3.48	67.32	58.27	108.2
10/16/96	14:04	SX698	979.7	54.0	21.18	4.14	16.97	3.46	66.99	58.69	109.0
10/16/96	14:07	SX698	976.8	49.5	20.94	4.00	16.67	3.38	67.17	56.30	104.5
Encapsulant: x15303p					S/N: 10		Location:		25		
12/5/96	12:01	SSI002	1049.2	43.6	20.71	4.15	16.13	3.47	65.20	56.04	100.0
12/5/96	12:04	SSI003	1049.5	39.6	20.58	4.06	16.06	3.39	65.27	54.49	97.2
12/5/96	12:08	SSI004	1052.1	44.2	20.82	4.02	16.27	3.39	65.92	55.16	98.4
12/5/96	12:10	SSI005	1048.7	41.8	20.80	4.09	16.37	3.44	66.23	56.32	100.5
Encapsulant: x15295p					S/N: 13		Location:		26		
12/5/96	12:14	SSI006	1053.4	46.9	20.67	3.97	16.34	3.38	67.29	55.16	100.0
12/5/96	12:17	SSI007	1050.8	49.6	21.03	4.08	16.77	3.45	67.33	57.79	104.8
12/5/96	12:21	SSI008	1055.6	49.9	21.31	4.07	16.94	3.43	67.01	58.09	105.3
12/5/96	12:25	SSI009	1053.2	47.1	21.19	3.93	16.84	3.34	67.42	56.20	101.9
Encapsulant: x9933p					S/N: 48		Location:		27		
3/27/97	11:55	SSI002	1073.7	47.1	20.97	4.13	16.45	3.47	65.88	57.05	100.0
3/27/97	12:01	SSI002	1061.8	46.9	21.05	4.07	16.88	3.36	66.16	56.75	99.5
3/27/97	12:06	SSI002	1061.6	47.2	20.52	4.02	16.32	3.33	65.89	54.31	95.2
3/27/97	12:11	SSI002	1069.6	43.8	20.55	4.08	16.19	3.44	66.40	55.69	97.6
Encapsulant: x9903p					S/N: 09		Location:		28		
3/27/97	12:27	SSI002	1071.4	50.1	21.93	3.95	17.82	3.34	68.73	59.51	100.0
3/27/97	12:41	SSI002	1068.7	48.2	20.44	4.06	16.06	3.47	67.07	55.66	93.5
3/27/97	12:23	SSI002	1067.5	50.1	20.75	4.09	16.27	3.48	66.73	56.65	95.2
3/27/97	12:18	SSI002	1063.1	47.7	20.75	3.94	16.66	3.30	67.23	54.97	92.4

Appendix D

Formulations for A9918P and 15295P

EVA-based Encapsulants

Material	Manufacturer	Parts by Weight	
		A9918P	**15295P**
Elvax 3185	DuPont	100	100
Lupersol 101	Pennwalt	1.5	--
Lupersol TBEC	Pennwalt	--	1.5
Cyasorb UV-531	American Cyanamid	0.3	0.3
Naugard P	Uniroyal	0.2	0.2
Tinuvin 770	Ciba Geigy	0.1	0.1
Z-6030	Dow Corning	0.25	0.25

Glossary of Materials and Abbreviations
Used In This Report

Term	Identification or Definition
A9918P	"Standard-cure" EVA-based encapsulant which is widely used in the industry for preparing crystalline and semi-crystalline type modules. The "P" indicates that the material contains Z-6030 silane coupling agent for adhesion and is thereby self-priming. A complete formulation appears in Appendix D.
15295P	"Fast-cure" EVA-based encapsulant which is increasingly being used in the industry for preparing crystalline and semi-crystalline type modules. The "P" indicates that the material contains Z-6030 silane coupling agent for adhesion and is thereby self-priming. A complete formulation appears in Appendix D.
Airphire	Former name for Solarphire (see below)
Ci35a	Xenon-arc type of Weather-O-Meter, accelerated aging device (Atlas Electric Devices Company)
Cyasorb UV-531	Hydroxy-benzophenone type UV absorber, which functions by taking the UV energy and converting it to heat in the infrared region (American Cyanamid)
Elvax 3185 and 150	Poly(ethylene-co-vinyl acetate) with 33% vinyl acetate by weight. Elvax 3185 is simply a purer grade of 150 and compositionally is the same. Elvax 3185 or 150 is used as the base resin in many EVA-based PV encapsulants, including A9918P, 15295P, and those which were identified during the field survey as having browned.
EMMA	Accelerated outdoor weathering exposure apparatus (equatorial mount with mirrors for acceleration) operated by DSET Laboratories in Phoenix, Arizona.
Lupersol 101	Peroxide crosslinker [2,5-dimethyl-2,5-di (t-butylperoxy) hexane].
Naugard P	Phosphite-type antioxidant that functions by decomposing peroxides (Uniroyal)

Term	Identification or Definition
Solite	Low iron glass with a stippled pattern on the underside, commonly used as a superstrate in PV modules (AFG Industries, Inc.). Glass made before about 1990 had no cerium dioxide in it; glass produced after that time does contain CeO_2 and is referred to as Solite II.
Solatex II	Low iron glass, slightly textured on both sides, containing CeO_2, used by some U.S. PV module producers as a superstrate (AFG Industries, Inc.).
Solarphire	Low iron glass, smooth on both sides, containing CeO_2 can be used as superstrate for PV modules (PPG Industries, Inc.). Formerly named Airphire.
Starphire	Low iron glass, smooth on both sides, without CeO_2 (PPG Industries, Inc.).
Tedlar	Fluoropolymer (polyvinyl fluoride) used as a film backing materials and sometimes a cover film for PV modules (DuPont).
Tefzel	Fluoropolymer [poly(ethylene-co-tetrafluoroethylene)] used as a cover film in some PV modules (DuPont).
Tinuvin 770	HALS (hindered amine light stabilizer) type UV stabilizer which functions by terminating the free-radical reactions that lead to photooxidative degradation (Ciba Geigy).
TPE	Laminate of Tedlar fluoropolymer film/polyester/and EVA resin, commonly used in the PV industry as a backing for modules.
Z-6030	Silane (methacyloxypropyl trimethoxy silane) type coupling agent that functions as an adhesion promoter for EVA to glass, cells, etc. (Dow Corning).

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OMB NO. 0704-0188

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1998	Final Report, January 1993–June 1997

4. TITLE AND SUBTITLE Advanced EVA-Based Encapsulants; Final Report, January 1993–June 1997	5. FUNDING NUMBERS C: ZAG-3-11219-02 TA: PV805101
6. AUTHOR(S) W.W. Holley and S.C.Agro	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) STR, Inc. One Springborn Center Enfield, CT 06082	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	10. SPONSORING/MONITORING AGENCY REPORT NUMBER SR-520-25296

11. SUPPLEMENTARY NOTES

NREL Technical Monitor: H. Thomas

12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161	12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report describes work performed by STR, Inc., under this Photovoltaic Manufacturing Technology (PVMaT) subcontract. The purpose of the three-phase PVMaT program was to further define the problem of EVA-based PV encapsulant yellowing in fielded modules, research possible chemical mechanisms, and then combat the yellowing phenomenon by developing advanced PV encapsulants. Phases I comprised a literature search on EVA-based encapsulant browning, survey of and site visits to installations reporting discolored encapsulant in fielded modules, and analysis of browned EVA-based encapsulant. During Phase II, development work, including reformulation, resulted in four experimental encapsulants with greatly reduced browning. After 40 weeks in the Weather-O-Meter, glass/glass laminates prepared with new formulations (standard and fast cure) showed no visible yellowing. During Phase III, these four experimental EVA-based encapsulants from Phase II were successfully prepared on a pilot scale using production equipment, and the resulting sheet was used, without significant problems, by six different module producers to fabricate full-size modules. With only a couple of exceptions, curing of these modules was at a consistently high level, with average gel content greater than 83%, versus a typical 80% for current EVA-based materials. STR will continue to keep these modules on outdoor test after the subcontract is completed.

14. SUBJECT TERMS photovoltaics ; Photovoltaic Manufacturing Technology ; PVMaT ; EVA-based encapsulants ; encapsulant discoloration ; encapsulant degradation ; modules	15. NUMBER OF PAGES 16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL