# DEVELOPMENT AND TESTING OF ADVANCED FIRE-RESISTANT PHOTOVOLTAIC MODULES

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## ABSTRACT

In response to the need for fire-resistant photovoltaic modules for certain applications, several advanced constructions have been developed using Kapton, metal foils, and high-temperature fiberglass rear-surface materials. Test results indicate that several configurations are capable of achieving Class B fire-resistance levels, and some Class A levels. The research effort, a cooperative, cost-sharing partnership between private industry and Federal participants, involved evaluating the flammability of existing commercial module designs, identifying design features that control flammability, and developing advanced fire-resistant module constructions. Simplification of standard fire testing procedures allowed rapid characterization of the fire resistance of large numbers of candidate constructions, and allowed video recording and detailed post-test analysis by the large number of contributing researchers.

Key Words: Flammability, Photovoltaics, Test Methods, High Temperature Materials

## INTRODUCTION

As part of the U.S. Department of Energy's National Photovoltaics Program, the Jet Propulsion Laboratory (JPL) Flat-Plate Solar Array Project is conducting research directed at future large-scale photovoltaic (PV) applications. One aspect of the JPL effort to improve PV module and array performance emphasizes the investigation of flammability characteristics of flat-plate PV modules that may contact external fire sources.

Roof-mounted residential and intermediate flat-plate PV array installations are expected to increase in number as PV modules become increasingly available on a large-scale basis. Safety-related building codes, as enforced by state and/or local officials, often require minimal fire-resistance levels for various applications, such as roof-mounted PV arrays on public buildings and certain residential communities with a high fire concern. These codes may categorize the PV array as a roofing material or require that the array not reduce the fire-resistance rating of a roof below required minimums. The National Fire Protection Agency (NFPA), in conjunction with Underwriters Laboratories, Inc. (UL), and the American Society for Testing and Materials (ASTM), has defined three specific fire-resistance ratings for roof-covering materials: Class A, effective against severe fire exposure; Class B, effective against moderate fire exposure; and Class C, effective against light fire exposure. The requirements and test procedures defining these ratings are identified in safety standards promulgated by organizations such as ASTM and UL (1).

Under contract to JPL to identify and develop system and component requirements that afford appropriate levels of safety, UL has identified two tests as applicable for PV manufacturers seeking to achieve a fire rating for their products: the spread-of-flame test and the burning-brand test (2). The spread-of-flame test is designed to measure resistance to flame spreading caused by an external source of flame impinging on the top surface of a PV array. The burning-brand test measures the ability of an array to resist penetration due to a burning brand. These two tests were used in this study.

### Photovoltaic Module Construction

The key to the photovoltaic technology is the solar cell, a semiconductor device that produces direct-current electricity when exposed to sunlight. The solar cells are connected in series to develop appropriate levels of voltage, and in parallel to develop higher levels of current. Groups of these interconnected cells are encapsulated into PV modules that provide basic building blocks for a PV array.

Current PV modules are constructed by laminating several materials to form an environmentally protected, essentially planar assembly of solar cells and ancillary parts, such as interconnects and terminals. In almost all modules currently being manufactured, the structural (load-carrying) member is the top layer (superstrate), typically 1/8-in.-thick tempered glass. Figure 1 shows a cross section of a representative superstrate design module, its generic elements, and typical ranges for material thicknesses (3).

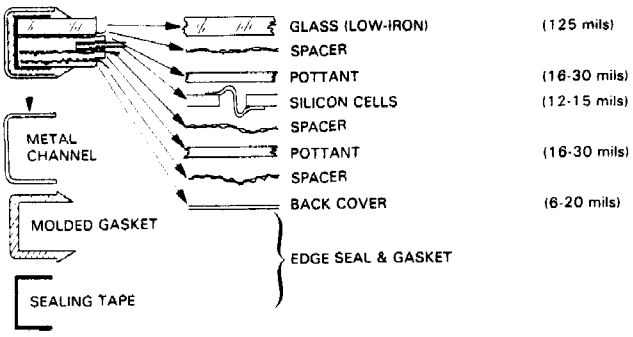


Figure 1. Cross Section of a representative superstrate PV module.

After the glass superstrate, the pottant is the thickest material in the laminate. To satisfy all of the major requirements placed on the pottant system, most module manufacturers are using pottants belonging to a class of materials known as hydrocarbons. These include ethylene vinyl acetate (EVA), polyvinyl butyral (PVB), and aliphatic polyurethane (AP). Back-surface materials consist of films, foils, and fabrics. The films used in current module designs are typically Tedlar, polyester, or laminates of these films, with or without a foil layer.

## Objective

Previous fire testing has disclosed that the module's hydrocarbon pottant is the most flammable module component. However, fire tests for roof-covering materials measure fire resistance in terms of the entire system response. Despite the pottant material's flammability, previous results of Class B burning-brand tests indicate that the module back-surface material is a critical element to successfully passing fire-resistance tests. This investigation thus focused on identifying back-surface materials and constructions capable of raising the fire resistance of modules using present hydrocarbon encapsulants to Class A and B levels.

The research involves evaluating the flammability of existing module designs, identifying module design features that control flammability, and identifying improved construction concepts and materials that achieve fire-resistant characteristics. A parallel investigation, complementing this activity, is researching means of reducing the flammability of encapsulant materials and identifying less flammable alternatives.

## Approach

The approach, shown in Figure 2, is a collaborative effort based on an iterative process that emphasized cost-sharing and simplifying relatively complex test procedures to enable cost-effective testing. UL, having complete fire test facilities and being active in the generation of electrical and fire safety standards, conducted the fire tests. Since measuring flammability performance of experimental test specimens was exploratory in nature and not an attempt at product qualification, UL helped to modify the test procedure to focus on key parameters affecting the test outcome and to allow rapid iteration of the tests.

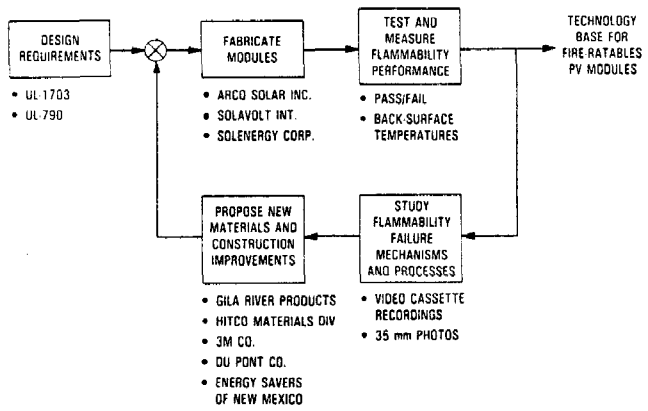


Figure 2. Approach to develop a technology base for fire-ratable modules.

Since the degree of flammability is strongly dependent upon both the specific materials of construction and their quantity, a variety of modules were tested to assess flammability performance of existing designs and to provide a generic understanding of flammability mechanisms. Videocassette recordings were used to study flammability failure mechanisms, and time-temperature profiles of the module back surfaces were used to identify requirements for candidate high-temperature materials. Identification of improved construction concepts and new materials involved coordination between material suppliers, who were unfamiliar with PV technology or the module construction interfaces, and module manufacturers, whose manufacturing processes are of a proprietary nature. Material suppliers were interested because of the opportunity for product development and the potential for sales in a new market; module manufacturers were able to gain valuable first-hand experience with new candidate materials.

Because the cost of flammability research is quite high, the cost-sharing nature of this activity was well received. JPL coordinated the effort, and located material suppliers and PV manufacturers interested in participating in the collaborative program. Gila River Products, HITCO Materials Division of Armco, 3M Co., Du Pont Co., and Energy Savers of New Mexico provided high-temperature materials to ARCO Solar, Inc., and Solavolt International, the companies that manufactured the experimental fire-resistant modules to be tested at UL.

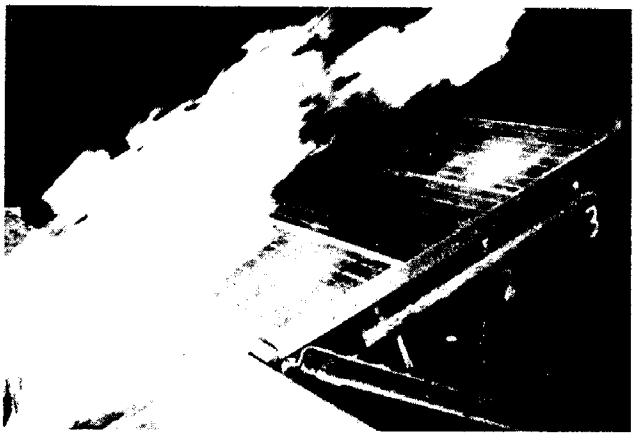

Figure 3. UL fire test apparatus with spread-of flame test in progress.

## FACILITIES AND TEST PROCEDURES

The UL fire test apparatus, Figure 3, consists of a steel framework whose pitch is adjustable, a blower and air duct for producing and controlling a 12±0.5 mi/h air current, and a gas burner for the spread-of-flame tests. A test deck to which the roof-covering material (PV modules, in this case) is applied, was normally not used. This deviation from the UL standard test procedure permitted access for detailed visual observation, and allowed video and time-temperature data to be taken from the module's back surface; it also eliminated the time and cost associated with building the deck and installing the photovoltaic modules. Additional facility equipment included a gas burner for igniting the burning brands, a velometer for wind velocity, a draft gauge for gas pressure, and a stopwatch.

### Burning-Brand Test Sequence and Constraints

The brands are constructed of kiln-dried Douglas fir strips (3/4 x 3/4 in.), free of knots and pitch pockets. Before placement on the test sample, the brand is ignited until it burns freely. This state is considered attained after the brand is subjected to a 1630±50°F flame for a specific period of time: five minutes for a Class A brand, and four minutes for a Class B brand. The brands are exposed to the flame in a specific manner and sequence. After the ignition phase, the brand is placed on the surface of the test sample at the location considered most vulnerable. Throughout the test, the blower and air duct provide a 12 mi/h air current across the top of the module and burning brand. Table 1 summarizes the key parameters of the burning-brand test, and Figure 4 provides a visual comparison of the size difference between the Class A and Class B brands.

For PV modules, only one test is required and only one brand is used. For these development tests, a single module was substituted for the typical roof section, which nominally consists of roof-covering material installed over a section 3 1/3 ft. wide by 4 1/3 ft. long. Additionally, the test is normally continued until any remaining embers are completely extinguished, approximately 45 minutes. To maximize use of the test facility, the tests were terminated 5 to 15 minutes after brand placement, which proved sufficient to characterize the results.

Table 1. Key parameters for burning-brand test, UL-790.

| Fire Rating | Burning-Brand Test | | |
|---|---|---|---|
| | Brand Size, in. | Brand Ignition Temperature, °F | Approximate Peak Module Temperature, °F |
| Class A | 12 x 12 x 2¼ | 1630 | 1900 |
| Class B | 6 x 6 x 2¼ | 1630 | 1400 |
| Class C | 1½ x 1½ x 25/32 | – | – |

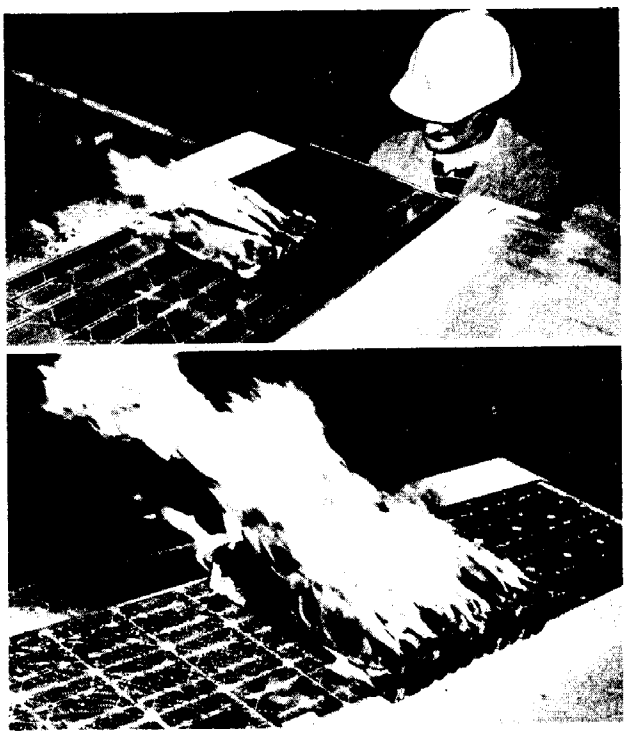

Figure 4. Visual comparison of Class A and B burning brands.

### Spread-of-Flame Test Sequence and Constraints

The gas burner used in this test is a 2-in.-dia. pipe 44 in. long, with a slot, 1/2 in. wide by 36 in. long, faced toward the test specimen. Gas is piped to both ends of the pipe to obtain uniform gas pressure. The burner is approximately 25 in. from the test sample and is influenced by the 12 mi/h air current. The gas supply produces 1400±50°F for Class A and B tests at a point

1 in. above the test sample, 1/2 in. toward the source of flame. These conditions result in a flame that extends about 4 1/3 ft., with licks of flame extending approximately 1 to 2 ft farther. The gas flame is applied for 10 min. or until the flaming of the test samples recedes from the point of maximum flame spread, whichever is shorter. Table 2 summarizes the key parameters of the spread-of-flame test, and Figure 3 shows a spread-of-flame test in progress using a partial, 3 ft. long roof section.

Table 2. Key parameters for spread-of-flame tests, UL 790.

| Fire Rating | Spread-of-Flame Test | | |
|---|---|---|---|
| | Flame Temperature, °F | Flame Application Time, min | Allowable Flame Spread Distance, ft |
| Class A | 1400 | 10 | ≤ 6 |
| Class B | 1400 | 10 | ≤ 8 |
| Class C | 1300 | 4 | ≤ 13 |

As in the case of burning-brand tests, a single module was usually substituted for a typical roof section, which normally consists of sample roof-covering material that measures 3 1/2 ft. wide by 9 ft. long for a Class B test and 8 ft. long for a Class A test.

Pass/Fail Criteria

In general, at no time during the spread-of-flame test or the burning-brand test shall any portion of the module be blown or fall off the test deck in the form of flaming or glowing brands, nor shall the roof deck be exposed by breaking, sliding, or cracking or warping of the roof covering, nor shall portions of the roof deck fall away in the form of glowing particles. In addition, the maximum allowable spread-of-flame distance is 6 ft. for a Class A test and 8 ft. for a Class B test. The burning-brand test is continued until flame, glow and smoke disappear. No sustained flaming on the underside of the deck or production of flaming or glowing brands of roof material is permitted.

Data Acquisition

Test monitoring equipment included a videocassette recording system, an infrared temperature-sensing device, and a 35 mm camera. In addition, detailed qualitative observations were provided by trained UL personnel. The video-cassette recording system consists of a tripod-mounted camera with a 10:1 zoom lens, connected to a portable VHS recorder. The recordings were used extensively in post-test reviews to study the failure mechanisms, taking full advantage of frame-by-frame, slow-motion, and stop-action capability. These features provided a convenient means of understanding and characterizing the combustion mechanisms.

The infrared temperature sensing device provided a simple and economical method of obtaining time-temperature profiles of candidate high-temperature back-surface materials. The temperature-monitoring device was normally sighted on a single point of the module back-surface material, but could be used to scan other points of interest, e.g., areas associated with bubbles formed on the back-surface material. Additionally, the 35 mm camera provided excellent visual material for presentations.

The data from these monitoring devices, when analyzed in conjunction with the UL data summaries of each test, allowed review by experts not able to witness the tests, shortened the data reduction phase and permitted selection of additional candidate materials that led to advanced module configurations.

## TEST RESULTS

A typical sequence of events resulting in failure is shown in Figure 5. This representative event profile, taken by infrared scan, plots module back-surface temperature versus time. After securing the ignited brand on the module, the glass superstrate begins to bow upward, and the back-surface material starts to separate, forming blisters. Approximately one minute after brand placement, the tempered-glass superstrate shatters and molten encapsulants and volatiles are ignited. After another minute the back cover ruptures due to failure mechanisms such as ripping or melting. Once the module back-surface integrity is lost, smoke and other volatiles are freely emitted, enabling the back of the module to burst into flame. The total sequence lasts an average of five minutes for a Class B brand, and less for a Class A brand. For comparison, the figure also shows the event profile for an experimental module that passed its test. Note that even though the glass cracked at about the same time, this sample's back surface did not rupture.

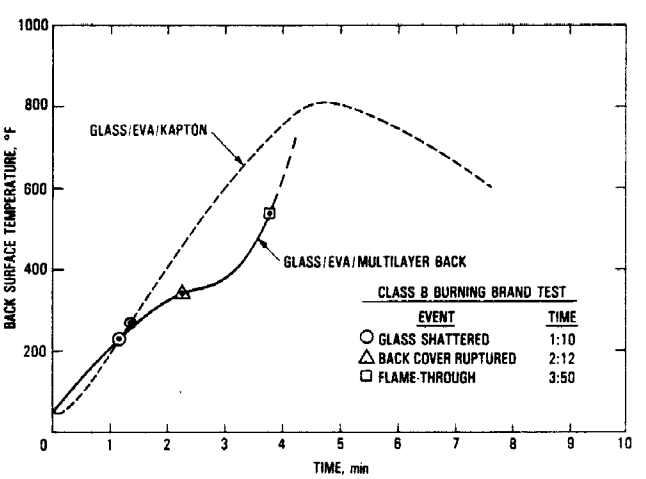


Figure 5. Event profile: back-surface temperature versus time.

Several key findings resulted from early module testing (4,5,6):

(1) Module integrity is difficult to maintain. When thermal stresses shatter the tempered-glass superstrate, combustible volatiles are released and the encapsulant is exposed to direct contact with the burning brand. A Tedlar and/or polyester rear film then melts, releasing combustibles into the space below the module. This penetration of the module back-surface material is catastrophic, resulting in total loss of integrity and subsequent dripping of flaming encapsulant.

(2) The heating due to a burning brand is a highly local phenomenon. Module thermal conductivity is relatively low, resulting in a severe temperature gradient in the vicinity of the brand. Figure 6, representative of data taken by infrared scan, shows isothermal contours of back-surface temperatures as a function of distance from the center of a Class B brand just before eruption. Note that the isothermal contour labeled 165°F is only 12 inches from the center of the brand, and although the back-surface area directly under the brand is at 515°F, the temperature of the top surface of the module is on the order of 1200°F.

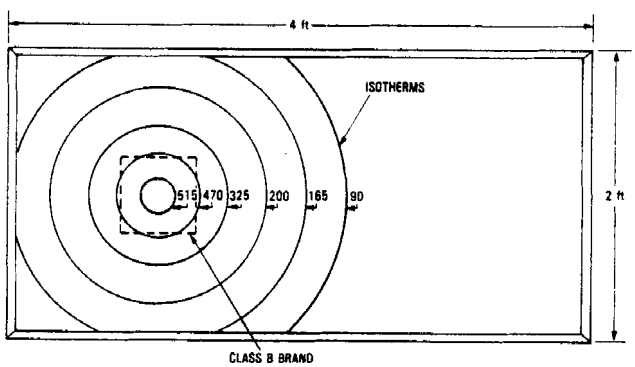


Figure 6. Back-surface temperature distribution for Class B brand.

(3) The maximum temperatures associated with the spread-of-flame test are not as severe as those associated with the burning-brand test. Figure 7 shows a comparison for a Class A spread-of-flame test and a Class A burning-brand test.

(4) Upon loss of module integrity, the time to failure (attic space exposed to flames) can be delayed by providing a continuous subroofing material beneath the module, and can be further delayed by blocking the joints between the subroofing panels (i.e., deck with blocked joints). This delaying effect is shown in Figure 8 for three modules that failed, as compared with a module that was mounted on a deck with blocked joints and whose back surface remained intact.

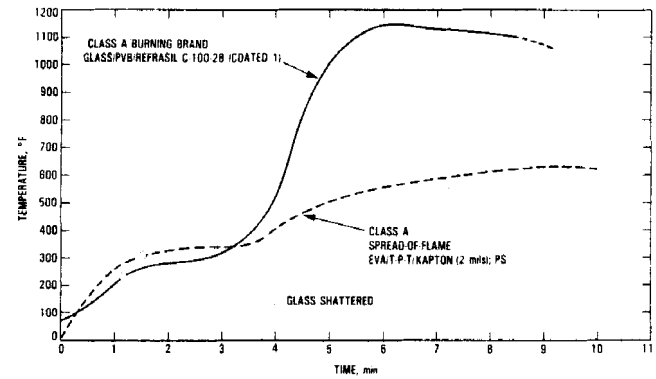


Figure 7. Comparison of Class A profiles; burning-brand versus spread-of-flame tests.

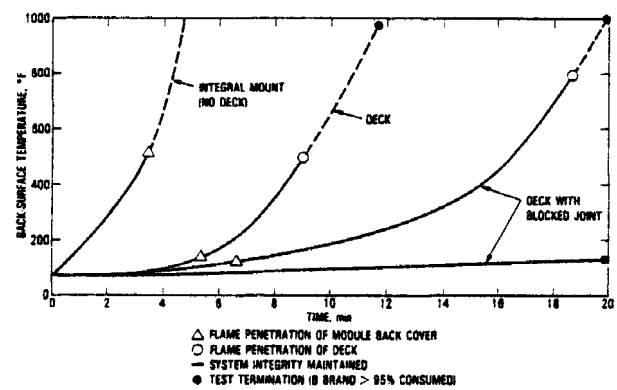


Figure 8. Effect of Continuous subroofing material beneath module.

These early findings suggested that the most promising approach was to improve module back-surface integrity through the use of high-temperature materials, and provided a basis that enabled the selection of a number of candidate materials including Kapton and high-temperature fiberglass cloths. Because data indicated that the spread-of-flame tests are not as severe as the burning-brand tests, emphasis was placed on the Class A and B burning-brand tests.

A summary of all tests, including description of high-temperature back-surface materials, is presented in Table 3. Note that, in some cases, module construction characteristics affected the outcome of a test. For example, Configuration 9 passed the Class B brand test while Configuration 10 failed. This was due to a pressure-sensitive adhesive system that permitted the shrinking Tedlar-polyethylene terephthalate-Tedlar (T-P-T) layer to separate from the Kapton, which has a high-temperature capability of 850°F - 1000°F, adequate for the Class B brand. The thermoset adhesive, on the other hand, bound the T-P-T layer to the Kapton, which, having relatively poor tear strength and very poor rip propagation characteristics, yielded when the T-P-T layer began to melt and shrink. In contrast to these cases, note that in Configurations 7 and 8, the larger volume of encapsulant provided enough fuel to permit temperatures in excess of 850°F where the Kapton failed.

Table 3. Description of Materials, Module Configurations, and Summary Results of Flammability Tests

| Module Pottant/Back-Cover Configuration* | Test Results** | | |
|---|---|---|---|
| | Flame | "B" Brand | "A" Brand |
| 1. EVA/Kapton (1 mil) | | 0 | |
| 2. PVB/Kapton (1 mil) | | 0 | |
| 3. PVB/A-Kapton (1 mil) | | 0 | |
| 4. PVB/T-A-T/Kapton (1 mil) | | 0 | |
| 5. PVB/T-A-T/A-Kapton (1 mil) | | 0 | |
| 6. EVA/Kapton (2 mils) | ● | ● | |
| 7. PVB/Kapton (2 mils) | | 0 | |
| 8. PVB/T-A-T/Kapton (2 mils) | | 0 | |
| 9. EVA/T-P-T/Kapton (2 mils); PS | ● | ● | 0 |
| 10. EVA/T-P-T/Kapton (2 mils); TS | | 0 | |
| 11. EVA/Kapton (3 mils) | ● | | 0 |
| 12. EVA/Kapton (3 mils); PS | ● | | 0 |
| 13. EVA/GRP | | 0 | |
| 14. PVB/GRP | | 0 | |
| 15. EVA/T (1 1/2 mils)-P(5 mils)-Black EVA(4%) | 0 | 0 | |
| 16. EVA/T-P-T/Energywave Paint (15 mils) | 0 | | |
| 17. EVA/Fiberglass-Fine-woven (stabilized) | | 0 | |
| 18. PVB/Refrasil (15 mil) | | | 0 |
| 19. PVB/T-A-T/Refrasil (15 mil) | | | 0 |
| 20. EVA/T-P-T/Fiberglass-Fine-woven (stabilized); TS | | ● | |
| 21. EVA/T-P-T/Fiberglass-Fine-woven (stabilized); PS | | 0 | |
| 22. EVA/Fiberglass-Silicon Rubber (1 side) | ● | ● | |
| 23. EVA/Fiberglass-Neoprene Rubber (1 side) | ● | ● | |
| 24. EVA/Fiberglass-Neoprene Rubber (2 sides) | 0 | | |
| 25. EVA/Refrasil-coated 1 side | | | ● |
| 26. PVB/Refrasil-coated 1 side | | | ● |
| 27. PVB/1584 Fiberglass-coated 2 sides | | | ● |
| 28. EVA/Aluminum (3 mils) in 4 layer laminate | | ● | 0 |
| 29. EVA/T-P-T/Stainless Steel (2 mils);PS | | | ● |

* PS-Pressure sensitive adhesive; TS-Thermoset adhesive; A-Aluminum; T-Tedlar; P-Polyethylene terephthalate; GRP-Gila River Proprietary;
** ●-Pass; 0-Fail

Another interesting example can be illustrated by comparing Configurations 25, 26 and 17. The Refrasil (a relatively expensive glass cloth) was coated with a proprietary high-temperature material that plugged the pores of the glass cloth. This candidate material, Configurations 25 and 26, successfully passed the Class A burning-brand test, while modules with other glass cloths, Configuration 17, were unable to pass the less severe Class B burning-brand test. In these cases the coating pyrolyzed, enabling the encapsulant to penetrate the porous glass cloth. Future tests will use other glass cloths coated with the proprietary, high-temperature material in an attempt to reduce costs further.

## SUMMARY

During the test program a variety of candidate materials were identified as consistent with achieving Class A and B fire ratings.

The 2-mil Kapton, in certain configurations, was sufficient to pass the Class B burning-brand test and the Class A spread-of-flame test, where back-surface temperature is around 900°F. The material stretched to contain the boiling pottants. In other 2-mil configurations, the low resistance to tear propagation, once the material was torn, resulted in failure to maintain module integrity. The 1-mil Kapton does not appear to

have sufficient strength to contain the boiling encapsulants. The Class A brand temperatures exceeded the temperature limitation of the 3-mil Kapton.

Two types of metal foil laminates showed promise. A 3-mil aluminum foil in a 4-layer laminate successfully passed the Class B burning-brand test, but failed to withstand Class A brand temperatures. A 2-mil stainless-steel foil would have passed the Class A burning-brand test if its edges had been better sealed. Although metal foils, especially stainless steel, are promising, the close proximity of a metallic surface to the PV circuit will require that the metal be electrically grounded for safety reasons.

Fiberglass cloths also achieved considerable success. Module configurations able to pass the Class B burning-brand test and the Class A spread-of-flame test used a fiberglass cloth that was coated or impregnated with a material that plugged the pores. Refrasil, a chemically processed fiberglass cloth, when impregnated with a high-temperature proprietary material, successfully passed the Class A burning-brand test although a large amount of gases was emitted. When failures occurred with glass cloths, they generally resulted from porosity of the material that permitted combustibles and volatiles to penetrate the back surface into the space below the module.

In addition to the technical successes in identifying fire-resistant module designs, the test approach also worked out exceedingly well. Program coordination by JPL brought together a number of diverse participants in a cost-sharing, collaborative program that has the potential of benefiting both material suppliers and the PV industry by making available new materials for use in fire-ratable PV modules. The simplification of costly and relatively complex test procedures to focus on the key elements and parameters affecting the test outcome led to effective use of the test facility. The videocassette recording system proved to be an effective means of enabling review and analysis of the data by the broad range of technical specialists and material suppliers. Future efforts will concentrate on more cost-effective materials and will assess fire-test impact on module edges and array joints.

## ACKNOWLEDGMENTS

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