FLAMMABILITY OF PHOTOVOLTAIC MODULES*

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ABSTRACT

A series of Class B burning-brand tests were performed on experimental modules using high-temperature, back-surface materials to develop the technology base required to construct fire-ratable modules. Results indicate the existence of synergistic relationships between hydrocarbon encapsulation materials and the experimental module configurations that provide increased fire resistance. These configurations use Kapton, fiberglass, neoprene rubber, stainless-steel foil or aluminum foil as the back surface. Successful test results occur when the structural integrity of the module back surface is maintained. Test failures of these modules always occur for one of three reasons: the outermost back cover melts, rips, or is too porous. In each case flammable molten encapsulant, its gaseous byproducts, or both, penetrates the back surface of the module and bursts into flame. Future efforts to complete the technology base will concentrate on the spread-of-flame test, focusing on the more promising configurations identified in the initial series of tests.

*This paper presents the results of one phase of research conducted at the Jet Propulsion Laboratory, California Institute of Technology, and sponsored by the U.S. Department of Energy, through an agreement with the National Aeronautics and Space Administration.

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INTRODUCTION

Part of the effort of the Jet Propulsion Laboratory (JPL) Flat-Plate Solar Array Project (FSA) includes a program to improve photovoltaic module and array performance. This paper describes one aspect of this program, which investigates the flammability characteristics of flat-plate modules. The issues related to module flammability are important to the photovoltaic community because of the potential for equipment damage, and in some cases, risk to human life.

Objective and Approach

The objective of this research program is to develop the technology base required to construct fire-ratable modules and subsequently to integrate them into safe arrays. This effort required the exploration and consideration of new materials of construction and module configurations to achieve increased fire resistance. Instead of a traditional materials approach that examines each module encapsulation construction element and its individual material properties, the focus has been on synergistic relationships within the entire module.

The research described in this paper has been divided into three test phases. Phase I, exploratory testing, was an early JPL assessment (June 1980 and August 1981) of the fire-resistance capability of then-current and emerging PV module designs that led to manufacturers' testing (1983) of commercial PV module designs. Phase II consisted of extensive parametric testing (January 1984) by JPL, aimed at understanding and characterizing PV module flammability mechanisms. Phase III included hypothesizing and testing improved module designs and construction techniques leading to increased fire resistance. A collaborative effort with ARCO Solar, Inc., enabled initial Phase III tests to be completed in February 1984.

Background

The nature of module flammability involves three distinct risk areas: (1) the ability of

a module to ignite itself from an electrical arc with flame then spreading beyond the arc site, possibly consuming the entire array; (2) the susceptibility of a module to ignition by an external flame such as a fire beneath or near the array or a flying ember; and (3) the extent to which a photovoltaic array affects the flammability of a sensitive application (such as a school roof) that requires special fire resistance.

For many applications, PV modules must be certified as being reasonably safe (listed) by a nationally-recognized testing organization, such as Underwriters Laboratories, Inc. (UL). The UL listing requires that PV modules be insensitive to ignition from arcs, but not necessarily from external flame sources. Product liability guidelines simply suggest that a PV array not present an unreasonable or unexpected fire risk.

For fire-rated applications, such as roof-mounted PV arrays on public buildings and in certain residential communities with a high fire concern, the National Fire Protection Association (NFPA), in conjunction with UL and the American Society for Testing and Materials (ASTM), has defined three specific fire-resistance ratings: 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 presented in safety standards, such as "Tests for Fire Resistance of Roof Covering Materials," UL-790.

The "Proposed Edition of the Standard for Flat-Plate Photovoltaic Modules and Panels," UL-1703, has identified two tests from UL-790 as applicable for PV module manufacturers seeking to achieve a fire rating for their products: the spread-of-flame test and the burning-brand test. The spread-of-flame test is designed to measure resistance to flame spread due to an external source of flame impinging on the top surface of a PV array. The burning-brand test measures the ability of a PV array to resist penetration due to burning brands. Table 1 summarizes the key parameters of each test.

The test apparatus consists of a steel framework for holding a test deck to which roof covering material and the PV array are applied. The deck may be additionally "blocked" with 2 x 4's at the decking material joints. The same framework is also employed without a deck to test integral-mount modules when the module serves as the sole roofing element. The framework and deck are inclined five vertical inches per horizontal foot and are subjected to a 12 ± 0.5 mi/h air current throughout the tests.

EXPLORATORY AND PARAMETRIC TESTS (PHASES I AND II)

As part of a contract with UL to identify and develop system and component requirements that would afford appropriate levels of safety, exploratory (Phase I) fire tests of PV modules were conducted in June 1980 and August 1981. Module constructions were typical of then-current and emerging designs: glass superstrate with silicone or Sylgard encapsulant; and fiberglass-reinforced polyester, Pan-L-Board or a corrosion-resistant steel pan as the back surface. Additionally, in the August 1981 tests, a module using a new encapsulant, ethylene vinyl acetate (EVA), was tested using a Class B burning brand.

Table 1. Key Test Parameters for the Spread-of-Flame Test and Burning-Brand Test--"Tests for Fire Resistance of Roof Covering Materials," UL-790

Fire Ratings	Spread-of-Flame Test*				Burning-Brand Test+		
	Flame Temperature, °F	Flame Application Time, min	Allowable Flame Spread Distance, ft	Size, in.	Brand Ignition Temperature, °F	Brand Ignition Time, min	Approx. Peak Brand Temperature, °F
Class A	1400 ± 50	10	≤6	12 x 12 x 2 1/4	1630 ± 50	5	1900
Class B	1400 ± 50	10	≤8	6 x 6 x 2 1/4	1630 ± 50	4	1400
Class C	1300 ± 50	4	≤13	1 1/2 x 1 1/2 x 25/32	-	2	-

*Spread-of-flame test: distance that flame has spread. No flaming or glowing brands of roof material.
+Burning-brand test: until flame, glow and smoke disappear. No sustained flaming on underside, production of flaming or glowing brands of roof material.

Results of these tests indicated that silicone modules are inherently fire-resistant to severe (Class A) fire exposure (spread-of-flame and burning-brand tests). Modules constructed of glass-EVA-Tedlar were not in widespread use at that time, but the test results indicated that modules using hydrocarbon encapsulants, such as EVA, are highly flammable, and may not be fire ratable.

By 1983, modules using a number of different hydrocarbon encapsulants, such as polyvinyl butyral (PVB), EVA, and aliphatic polyurethane (AP), were commonplace. PV manufacturers proceeded to obtain fire ratings and certification for certain PV module designs within their product lines. Results of these efforts varied, with one manufacturer obtaining a Class C fire rating for a hydrocarbon encapsulant module, and a competitor failing to obtain a Class C rating using the identical encapsulation material. Many questions were raised regarding the degree of flammability of various hydrocarbon encapsulant materials.

To respond to these and other questions, a series of parametric tests (Phase II) were performed in January, 1984, specifically to address and characterize the nature of flammability for PV modules subjected to the Class B burning-brand test. A total of 27 burning-brand tests were conducted, using PV modules from nine different manufacturers, including residential, intermediate and central station designs. Module construction varied, using three encapsulants, EVA, PVB and AP, in combination with seven different back-surface materials. Table 2 presents key features of the modules tested and summarizes results.

Several points should be noted concerning the method in which these and subsequent tests were performed. Normally, in an actual test per UL-790, the PV modules would be mounted per the manufacturers instructions on a typical roof. For example, a direct-mount array might involve a half-inch-thick plywood deck covered with Class B roofing paper, over which the PV modules are fastened mechanically. In almost all of the Phase II and Phase III tests however, the modules were placed directly on the steel framework of the test apparatus, enabling ready access to the back surface of the module. This permitted the use of an infrared (IR) scanning device to monitor module back-surface temperatures and enabled unobstructed visual observation. 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 stopped 10 to 15 minutes after brand placement, which proved sufficient to characterize the result.

As experienced in earlier tests, most Phase II modules were unable to pass the Class B burning-brand test. The failures resulted from high temperatures causing the loss of module back-surface integrity, allowing flammable encapsulant and combustible volatiles to penetrate into the space below.

A typical sequence of events resulting in failure is as follows. After the ignited brand is secured on the module, the glass superstrate begins to bow upward, and the back-surface material starts to separate from the encapsulant, forming blisters. On the order of one minute after brand placement, the tempered glass superstrate shatters and liquid encapsulants and volatiles are ignited by the brand. 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. Approximately 1 1/2 minutes after rupture, the back of the module bursts into flame. The total sequence lasts an average of five minutes. Figure 1 shows this representative event profile, plotting back-surface temperatures, taken by an IR scan, versus time. For comparison, the event profile for an experimental module that passed its test is also shown. Note that this sample's back surface did not rupture.

Several key findings resulted from this series of failures. First, it is difficult to maintain module integrity. The tempered-glass superstrate shatters due to thermal stress, resulting in the release of combustible volatiles and exposure of the encapsulant to direct contact with the burning brand. Additionally, penetration of the module back-surface material is disastrous, resulting in total loss of integrity and subsequent dripping of flaming encapsulant. Second, hydrocarbon encapsulants (EVA, AP and PVB) are highly, and from visual observation appear equally, flammable.

Third, in the event of loss of module integrity, the time to failure (attic space exposed to flames) can be delayed by providing a continuous subroofing material, and can be further delayed by blocking the joints between the sub-roofing panels (i.e., deck with blocked joints). This delaying effect is shown in Figure 2 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.

Fourth, the degree of heating due to the brand is a highly localized phenomenon. The module thermal conductivity is relatively low, resulting in a severe temperature gradient in the vicinity of the brand. Figure 3 is representative of data taken by IR scans and shows isothermal contours of back-surface temperatures as a function of distance from the center of a Class B brand just before the eruption of flame. 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.

Although the majority of tests resulted in failure, a few modules managed to pass. In these cases the module back-surface integrity was maintained, at least to the point of allowing only smoke and volatiles to penetrate the back surface. The maximum temperatures were on the order of 850°F.

Table 2. Description of GLass Superstrate Modules and Summary of Phase II Parametric Fire Tests

MFR	Encapsulant System*	Nominal Size, ft	Test Configurations**	Results of Summary***
A	EVA/T	2 x 4	B/O; B/OBJ	F; F
A	EVA/T	2 x 4	B/O; B/O; B/O	F; F; F
B	EVA/T	2 x 4	B/O	F
C	EVA/T-P-T	1 1/2 x 4	B/O	F
B	EVA/T-P-T	1 x 4	B/OBJ	F
D	EVA/PFPS-T-Al-T	1 1/2 x 4	B/O; B/O	F; F
E	PVB/T	2 1/2 x 4	B/O; B/O	F; F
C	PVB/T-Al-T	1 1/2 x 4	B/O; B/O; B/O	F; F; F
F	PVB/T-Al-T	1 x 4	B/O	F
G	EVA/T-Al-RBC	1 1/2 x 4	B/O; B/O; B/O; B/O	P; F; P; P
H	AP/Glass	1 1/2 x 3 1/2	B/O; B/O	P; P
I	PVB/T-P-T/SS	1 x 2 1/2	B/O; A/O	P; P

*Encapsulant System Codes:
EVA – Ethylene vinyl acetate
PVB – Polyvinyl butyral
AP – Aliphatic polyurethane
T – Tedlar
P – Polyethylene terephthalate film
Al – Al foil
RBC – Rubberized back coating
PFPS – Polyester fiber porous spacer
SS – Stainless steel

**Test Configuration Codes:
B/O – 'B' brand/open back
B/OBJ – 'B' brand/dock with blocked joist
B/O – 'B' brand/dock
A/O – 'A' brand/dock

***Results of Summary Code:
F – Fail
P – Pass

EXPERIMENTAL FIRE-RESISTANT MODULES (PHASE III)

Following the series of parametric tests, ARCO Solar Inc. and JPL agreed to collaborate on a joint program to fabricate and test experimental modules using high-temperature back-surface materials and improved module construction techniques. The purpose was to examine how different back-surface materials were affected and whether module construction techniques might effect greater resistance to flammability for PV modules with hydrocarbon resin pottants.

Five types of back-surface materials were evaluated: Kapton aromatic polyimide film, two kinds of woven fiberglass cloth, Neoprene rubber (as both a molded sheet and a latex coating), stainless-steel foil and aluminum foil. The aluminum was tested as part of a four-layer composite. Where the flame-resistant layer was either an electrical insulator or was electrically isolated from the PV circuit, the material was configured as a substitute back cover as well as an add on layer over ARCO's present back-surface material, which is a Tedlar-polyethylene terephthalate-Tedlar (T-P-T) composite. Two different adhesives, a thermosetting type (TS) and a pressure-sensitive type (PS), were tested for bonding the additional flame-proof materials to this standard back cover.

Table 3 contains the materials descriptions and estimated materials costs of the various flame-retardant back layers tested. The information is expressed in terms of the module configuration, and a summary of the test results expressed in terms of whether the result would likely have been a pass or fail if the test had been run under standard conditions of duration and mounting configuration.

Kapton

The Kapton tested in this series was type 200H, which is an unfilled, 2-mil-thick, general-purpose grade of Kapton. Its color is a transparent amber and it appears to bond adequately to Tedlar with either the TS or the PS adhesive.

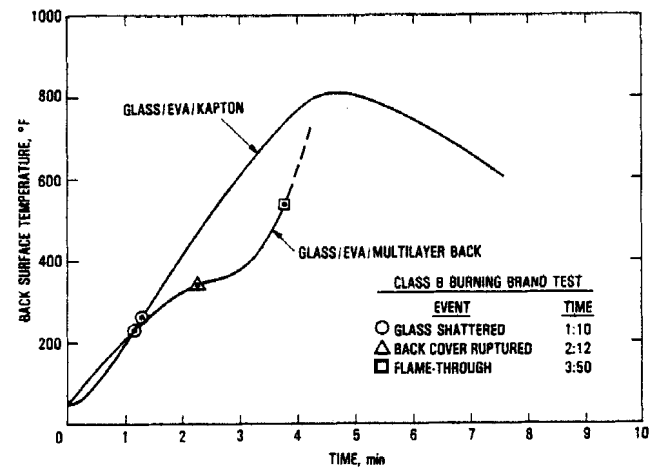

Figure 1. Event Profile: Back-surface Temperature versus Time

Adhesion directly to EVA without an intervening adhesive layer is fair at 4 to 5 lb/in. peel strength.

Kapton did not melt at the highest temperatures (836°F) reached by the back side of the modules. It simply stretched to a large bubble and contained the flammable, molten EVA when it was bonded directly to EVA as the back cover (module No. 1) and when it was bonded to a T-P-T composite with the relatively weak PS adhesive (module No. 2). Modules No. 1 and No. 2 both passed the Class B burning-brand test. Module No. 3, bonded with the TS adhesive, failed the Class B test because the Kapton ripped.

In module No. 3, the Kapton was firmly bonded to the relatively stiff T-P-T composite back cover with the TS adhesive. From previous ARCO work, some PS adhesives are known to dissolve or at

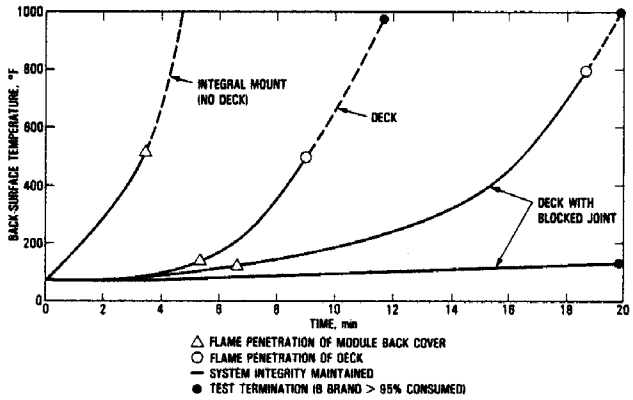

Figure 2. IR Scan of Back Cover Temperature versus Time

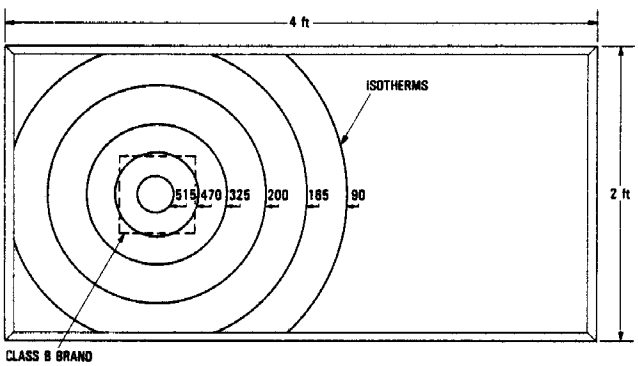

Figure 3. IR Scan of Back-Surface Temperatures Just Before Flaming, °F

least swell in molten EVA, thus losing simultaneously their bond strength and their stress-concentrating ability. The TS adhesive, on the other hand, crosslinks upon exposure to sufficient heat. Kapton bonded with it ripped fairly early in the test. Thus the strong, non-softening TS adhesive bond between the Kapton and the T-P-T composite must have transferred enough stress from the shrinking, melting, and relatively tough back cover to exceed the rather low-tear strength of the 2-mil Kapton.

Woven Fiberglass

Two types of woven fiberglass were tested. The first was a dimensionally stabilized, densely woven fiberglass (uncoated Beta cloth) made from finer filament yarn than is ordinary fiberglass. It is more flexible in mechanical handling, resulting in fewer broken fibers and higher tear strength. Samples of ordinary, very inexpensive (< $0.20/ft^2) fiberglass cloth were also used. The latter samples differed in the degree of coarseness or weave density and in the type of weave rather than in filament size.

According to the vendors, the glass used in all of these samples was ordinary window glass (soda-lime float glass), with distortion temperatures on the order of 1100°F, which appeared to be sufficient for use on the back of a PV module intended to pass the Class B burning-brand test. The main problem with all of the fiberglass materials was porosity.

The uncoated Beta cloth passed the Class B burning-brand test when bonded to the T-P-T composite back cover with the TS adhesive, which plugged its small pores (module No. 4). It failed as a direct substitute back cover (module No. 5) and when bonded to the T-P-T composite with the low bond strength, EVA-soluble, PS adhesive (module No. 6). The fine-weave ordinary fiberglass, bonded to the T-P-T composite with the PS adhesive, also failed (module No. 7). In all the fiberglass failures, molten EVA seeped through the back cover, or resulted in vigorously burning volatiles exiting the back, or both.

With the coarsely woven ordinary fiberglass bonded to the T-P-T composite (module No. 8), even the TS adhesive could not plug the large (approximately 1/16 inch) pores in the cloth sufficiently to prevent penetration by burning volatiles. This module also failed. No burning liquid EVA dripped through module No. 8, however, which is consistent with the results using TS adhesive bonded to the uncoated Beta cloth on module No. 4. It appears that only the high-pressure burning volatiles were able to break through the TS adhesive layer, probably because it was less densely supported mechanically by this fiberglass than by the tighter-woven uncoated Beta cloth.

Neoprene Rubber

Two approaches involved applying a highly crosslinked chlorocarbon (Neoprene) rubber layer to the backs of PV modules to prevent leakage of flammable hydrocarbon liquids and volatile byproducts. In one case a cured sheet was glued to a standard module with TS adhesive (module No.9), and in the other a much thinner latex coating was applied onto a module back that had been primed for adhesion (module No. 10).

Samples of Neoprene compounded for maximum flame retardancy could not be obtained in time for testing, so samples of both a cured sheet of mineral-filled Neoprene and a standard ZnO-cured Neoprene latex were used. According to the Du Pont Co., for maximum flame retardancy a formulation in either the molded cured sheet or latex form should use Neoprene with the highest chlorine content available and should contain at least 3 parts per hundred resin (phr) antimony trioxide, 6 phr hydrated alumina, all other fillers of mineral character, and plasticizers, if used, of chlorinated hydrocarbon wax character.

The Neoprene sheet on module No. 9 was 93 mils thick and was fully cured. The latex coating

Table 3. Description of Materials, Module Configurations, and Results Summary of ARCO-JPL Fire Tests

Module	Material Description	Cost, $/ft2	Configuration	Adhesive*	Results**
1	Unfilled Kapton (2 mils)	1.05	Substitute	-	P
2	Unfilled Kapton (2 mils)	1.05	Add-on	PS	P
3	Unfilled Kapton (2 mils)	1.05	Add-on	TS	F
4	Fiberglass - fine-woven (stabilized)	0.85	Add-on	TS	P
5	Fiberglass - fine-woven (stabilized)	0.85	Substitute	-	F
6	Fiberglass - fine-woven (stabilized)	0.85	Add-on	PS	F
7	Fiberglass - fine-woven (unstabilized)	0.20	Add-on	PS	F
8	Fiberglass - coarse-woven (unstabilized)	0.20	Add-on	TS	F^+
	Neoprene Rubber (mineral-filled) -				
9	Sheet (93 mils)	1.50	Add-on	TS	P
10	Latex (8 mils)	0.25	Add-on	-	F
11	Stainless-Steel Foil (2 mils)	0.45	Add-on	TS	P
12	Stainless-Steel Foil (2 mils)	0.45	Add-on	PS	AP
13	Aluminum Foil (3 mils) in 4-layer laminate	0.08	Substitute	-	P
14	Aluminum Foil (3 mils) in 4-layer laminate	0.08	Substitute	-	AF

*Adhesive Codes: PS - Pressure Sensitive; TS - Thermoset

**Result Codes: Class B burning brands except modules No. 12 and 14.
P - Pass; F - Fail; F^+ - burning volatiles only; AP - Class A brand: Pass; AF - Class A brands fail.

applied to module No. 10 had an average thickness of 8 mils and completeness of cure was questionable. Module No. 9 passed the Class B burning-brand test; module No. 10 failed, more likely because the rubber melted than because of inadequate thickness.

Stainless-Steel Foil

Type 321 2-mil stainless-steel (SS) foil applied to the back of the standard module enabled it to pass not only a Class B burning-brand test (module No. 11), but also tentatively to pass a Class A burning-brand test (module No. 12). The result on module No. 12 was a tentative pass because although the back surface remained totally intact, a tiny amount of low-intensity flame-through occurred at the lower edge of the module for about 2.5 minutes during the test. This small amount of flame-through from burning edge sealant may be enough to cause deck ignition and test failure. With a melting point in excess of 2550°F, the SS foil could be expected to resist the Class A brand temperatures.

Aluminum Foil

Type 1100 3-mil aluminum foil was tested as part of a four-layer composite configured as a substitute back cover. The economics of this approach make it attractive from the standpoint of materials cost and one-step processing. However, as with SS foil or any other metallic surface used in proximity to the PV circuit, this approach has the additional complication of requiring the metal to be electrically grounded for safety reasons, and cost is more difficult to estimate.

The thick aluminum composite resulted in a module that passed the Class B burning-brand test but failed the Class A test. This is not surprising, since the Class B brand reaches a peak temperature that is only about 194°F higher than the melting point of aluminum. The Class A brand is almost 752°F hotter than the melting point of aluminum.

SUMMARY

Analysis of the results indicates the existence of synergistic relationships between the encapsulation materials and the module configuration that provide increased fire resistance. In these tests, successful results occurred when the structural integrity of the module back-surface was maintained. Failure of a PV module with a hydrocarbon resin pottant always occurred for one of three reasons; the outermost back cover melted, ripped or was too porous. In each case large quantities of flammable molten encapsulant or byproducts (such as acetic acid in the case of EVA), or both, penetrated the back surface of the module and burst into flame. A flame-through of any significant duration was considered a test failure, since given enough time, it would cause ignition and penetration of flammable subroof materials beneath it.

Tedlar or polyester film, or combinations thereof, fail because they melt. Ripping of the outer layer does not necessarily cause failure unless the rip propagates. In the case of a highly crosslinked, tough, rubbery membrane, a few small initial splits appear to allow release of the pressurized volatiles (e.g. smoke) without a massive release of flammable liquid material because the rips do not propagate in a high-tear-strength rubber. On the other hand, most hard, high-modulus, low-flexibility materials such as Kapton, especially in thin-film form, have a high resistance to tear initiation but propagate rips much more easily once they start because of very low resistance to tear-propagation. Porous woven fiberglass or other high-temperature fiber cloths do not easily rip or melt, but fail unless they are woven very tightly and consist of fibers that are not well wetted by molten encapsulants. The porosity, if it is not too gross, can be plugged with thermosetting resins, adhesives or surface treatments that reduce fiber wettability by raising the interfacial tension.

Class B Rating

Of the five types of materials tested, none should be eliminated from further consideration for a Class B rating, although certain configurations of those approaches can be eliminated. They include Kapton bonded to Tedlar or polyester films with any kind of rigid, thermosetting adhesive that could concentrate tear stresses; any non-densely woven fiberglass; densely woven fiberglass with hydrocarbon-wettable fibers and/or that are bonded with softening, nonthermosetting hydrocarbon-soluble or wettable adhesives; Neoprene rubber that is undercured, too thin and/or not of optimum fire-retardancy compounding; flammable rubber edge sealants; and very thin (<1.0 mil), low-tear-strength aluminum foil.

Class A Rating

Aluminum foil in all forms can be eliminated for a Class A rating. It cannot withstand the Class A brand temperatures. Stainless-steel foil will meet Class A requirements with the proper edge sealing. Densely woven, nonwettable fiberglass probably has a better chance of passing than Kapton or maximum flame-retardant, highly cured Neoprene rubber.

FUTURE WORK

Future efforts will concentrate on the Class B and Class A spread-of-flame test and the Class A burning-brand test, focusing on the more promising configurations, including thick aluminum foil (Class B only); softly bonded Kapton; nonwettable (by hydrocarbon encapsulants), densely woven fiberglass; highly crosslinked Neoprene sheet or latex compounded for maximum flame retardancy, and stainless steel-foil (2-mil). Additionally, certain combinations of these high-temperature materials, such as Kapton with fiberglass, appear promising and remain to be researched.

ACKNOWLEDGEMENTS

The authors would like to express their appreciation to John Pabian of Underwriters Laboratories, Inc., and Richard Bundy and Sam Canale of ARCO Solar, Inc., for their assistance.