SIMULATED HAIL IMPACT TESTING OF PHOTOVOLTAIC SOLAR PANELS

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ABSTRACT

As part of the Jet Propulsion Laboratory's Low-Cost Silicon Solar Array Project, test methods have been evaluated and procedures developed for testing photovoltaic flat-plate solar cell modules for resistance to impact by hail stones. Testing has included the use of simulated hail stones (frozen ice spheres projected at terminal velocity), steel balls, and other projectile types applied with three loading methods: air guns, gravity drop, and static loading. Results are presented that compare the advantages and disadvantages of the three test methods. Dropped-steel-ball tests are shown to exhibit little correlation with high-velocity ice-ball tests, whereas statically loaded steel balls are shown to correlate fairly well with ice-ball tests. Results are also presented on the hail impact strength of ten commercially available flat-plate photovoltaic modules. In general, the module designs are shown to be capable of withstanding hail up to 1 in. diameter. Present glass modules are found to be slightly more rugged than modules with silicone rubber front surfaces, but not as rugged as modules made from acrylic sheet. The critical failure mechanism of each module type is explored and means for improving the hail resistance of future modules are described.

INTRODUCTION

Though solar photovoltaic arrays have been used for many years as a primary source of power for space vehicles, the terrestrial use of photovoltaics has come into prominance only within the last couple of years. In support of decreased dependence on our limited fossil and nuclear fuel supplies, the U.S. Department of Energy has an active program that addresses the greatly expanded development and utilization of terrestrial photovoltaic systems. A major part of the National Photovoltaic Program is centered at the Jet Propulsion Laboratory, and is referred to as the Low-Cost Silicon Solar Array (LSSA) Project. One aspect of the LSSA Project involves the analysis of the current state of terrestrial photovoltaic technology and the development of future array requirements.

Until recently, hail was recognized as an environment that must be considered in the design of solar arrays, but was generally considered of low priority. With the development of the largest photovoltaic system to date, (25 kW) in Mead, Nebraska, and an even larger system (250 kW) in progress for the Mississippi County Community College in Arkansas (both severe hail areas), increased importance has been placed on the damage potential of hail. In response to this importance, a portion of the engineering activities of the LSSA Project have been directed at understanding the hail environment and defining environmental design criteria including qualification test procedures. Review of the available literature and discussions with numerous specialists in the field of hail have indicated a lack of data characterizing the hail environment and a lack of hail design criteria and test standards. As a result, a four-phased effort was conducted with the following objectives:

(1) Define the hail resistance of current photovoltaic module designs.

(2) Define design changes and costs associated with improving module hail resistance.

(3) Develop hail testing procedures appropriate for environmental qualification tests.

(4) Characterize the natural hail environment.

(5) Explore the life-cycle cost effectiveness of various degrees of hail resistance to support the definition of appropriate design criteria.

This paper describes the preliminary results associated with the first three objectives listed above. A companion paper presents the results of the study characterizing the natural hail environment (Refs. 1 and 2). The life-cycle cost analyses are presently in work and will be the subject of a

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future paper on photovoltaic module design criteria for hail.

HAIL IMPACT SIMULATION

In simulating impact phenomena, the weight, velocity, material properties (hardness, strength, stiffness, etc.), and geometry of both target and projectile are important. To establish the hail impact strength of current commercially available photovoltaic panels it was decided, therefore, to duplicate all of the above parameters as closely as possible by impacting molded ice spheres on actual solar panels at velocities corresponding to the terminal velocity of naturally occurring hail. The question of whether a molded ice sphere adequately simulates naturally occurring hail remains.

Of 10 Illinois hail storms studied by Changnon (Ref. 3), 5 were accompanied by winds in the SW-NW quadrant, while 5 were accompanied by winds in the NW-NE quadrant, the median wind direction being NW. Photovoltaic solar panels are generally installed at 30 to 45 deg to the horizontal with southern exposure. If most hail is accompanied by northerly winds, the panels will receive only glancing blows. On the other hand, if the hailstones come from the south borne by a wind whose velocity is equal to the vertical terminal velocity of the hailstones, the hailstones will have a velocity 1.414 times their vertical terminal velocity. The kinetic energy of these hailstones will be twice that of the same hailstones in still air. They will impact normal to the surface of a solar panel tilted 45 deg to the horizon. From the standpoint of hail damage risk to photovoltaic solar panels, then, northerly winds will tend to decrease damage and southerly winds will increase damage. Avoiding ultraconservatism, we decided to impact the panels normal to their surface with simulated hailstones at still air terminal velocities.

Table 1 gives the weight, terminal velocity, kinetic energy, and momentum for hailstones ranging in size from 0.50 to 3.00 in. diameter. To construct this table, the commonly reported value of 0.9 g/cc is taken as the density of hail. The terminal velocities, v_T, are obtained from equation 1, below, which is readily derived by equating the weight and aerodynamic drag of a sphere.

$$v_T = \sqrt{\frac{4\rho_H \, dg}{3\rho_A \, C_D}} \qquad (1)$$

where

C_D = drag coefficient of sphere

d = diameter of hailstone

g = acceleration of gravity

ρ_A = density of air

ρ_H = density of hail

The velocities so obtained, taking $C_D = 0.47$, are slightly higher than those reported by Friedman (Ref. 4). To put this information in perspective, the same quantities are reported for several familiar sports balls, human propelled, at world record speeds.

Examination of Table 1 shows that while the diameter of the hailstones shown (0.5 to 3.0 in.) varies by a factor of 6, the weight varies by a

Table 1. Weight, velocity, and kinetic energy of hailstones and other objects

Object	Diameter, in.	Weight, lb	Terminal Velocity, mph	Kinetic Energy, ft-lb	Momentum, lb-s
Hailstone	0.50	0.00213	36.4	0.094	0.0035
Hailstone	0.75	0.00718	44.6	0.476	0.0146
Hailstone	1.00	0.01702	51.5	1.51	0.0399
Hailstone	1.25	0.0332	57.5	3.67	0.0871
Hailstone	1.50	0.0574	63.0	7.62	0.165
Hailstone	2.00	0.1361	72.8	24.1	0.451
Hailstone	2.50	0.2659	81.3	58.8	0.986
Hailstone	3.00	0.4595	89.1	122.0	1.87
Baseball (Refs. 8, 9)	2.90	0.320	101[a]	109.1	1.47
Softball (Ref. 8)	3.82	0.414	>100[b]	138.4	1.89
Tennisball (Refs. 10, 11)	2.56	0.127	137[c]	79.7	0.793

[a]Thrown by Nolan Ryan.

[b]Thrown by Eddie Feigner.

[c]Served by Scott Carnahan.

factor of over 200, and the kinetic energy by a factor of nearly 1500. Also note that 2 in. diameter hailstones have only about one-fourth the kinetic energy of the human propelled objects shown.

SIMULATED HAIL IMPACT TEST APPARATUS

The apparatus used to manufacture hailstones and project them at the photovoltaic solar panels is similar to that used by other investigators (Refs. 5, 6, and 7). This equipment consists of simulated hailstone molds, a freezer, a pneumatic gun, and a velocity measuring system.

The mold for making ice spheres was obtained from a previous JPL program (Ref. 5) of the mid 1960s where hail impact on antenna reflecting surfaces was studied. This mold, shown in Fig. 1, has a hemispherical cavity of the appropriate size in each of the aluminum mold halves. The mold is opened, a piece of ice somewhat larger than the desired hailstone is inserted, and a combination of heat and pressure is used to mold the ice into a sphere as the mold is closed. Immediately after forming, the ice ball is placed in a freezer where they are "stabilized" at 18°F for a minimum of 8 hours prior to use. The useful life of the ice balls stored in this manner is less than a week due to sublimation. Greenfeld (Ref. 6) and Smith (Ref. 7) use casting techniques to form the ice spheres, but the ice balls are stored in the same manner.

A pneumatic gun, shown in Fig. 2, was constructed to fire the simulated hailstones at the solar panels. To simplify aiming, the gun fires vertically upward at the target solar panel which is mounted overhead. The gun consists of a large (≈ 2 ft^3) reservoir, which is prepressurized with compressed air to the desired firing pressure. An opening in the top of the tank is equipped with a large, fast-opening solenoid valve. Interchangeable barrels for the various hailstone sizes are fitted directly to this valve. The barrels are 3 ft long and constructed of standard pipe. In operation, an ice ball slightly larger than the barrel bore is placed at the muzzle (top) of the barrel. Melting and gravity cause the ice ball to fall gently to the breech (bottom) of the barrel at which time the fast-opening valve is opened, admitting the compressed air to the barrel and propelling the ice ball vertically upward at the target. To verify that the simulated hailstones achieve the desired velocity, a photo-electric velocity measuring system is installed between the muzzle of the gun and the test article.

DESCRIPTION OF PANELS TESTED

In general, a terrestrial photovoltaic solar panel consists of an array of thin silicon solar cells electrically connected in various series/parallel combinations to provide the desired output voltage. The cells are encapsulated in a dielectric to isolate them electrically and to protect them from the elements. In addition, some means is required to support the cells under the environmental

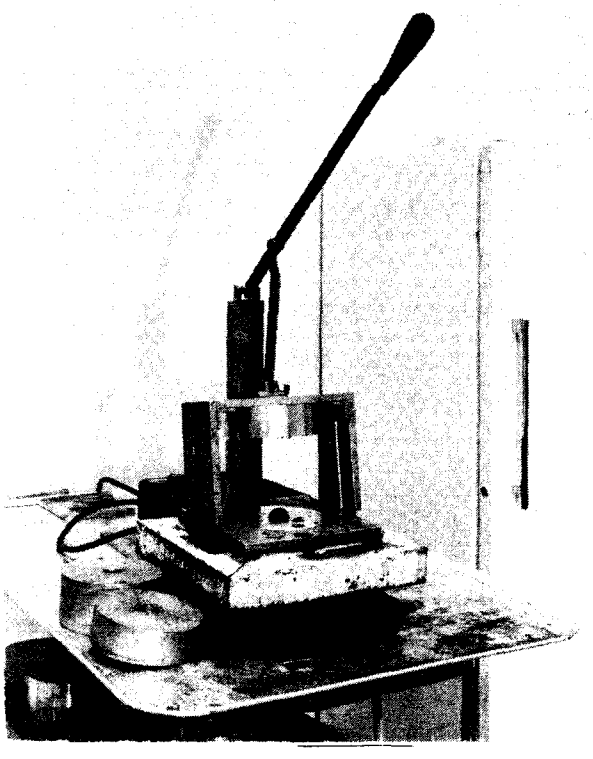


Fig. 1. Simulated hailstone mold

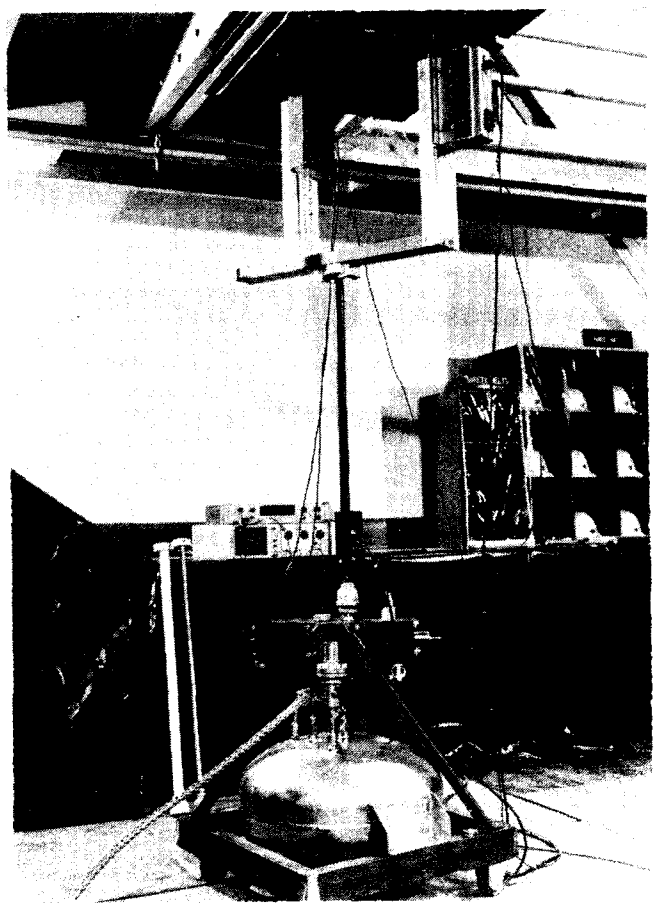


Fig. 2. Pneumatic hail gun

loads. A total of 10 commercially available panel designs from 5 manufacturers were tested. In some cases, more than 1 panel of a given design was tested.

Figure 3 shows the 10 panels tested, and a brief physical description of the panels is provided in Table 2.

Some additional discussion of the salient design features of these modules is considered necessary to better understand the failures resulting from the simulated hail impact reported later. Solar panel Type AI, which employs acrylic sheets top and bottom to support the cells and protect them from the elements, did not employ an encapsulant per se. The cells were bonded to the bottom sheet of acrylic and the top sheet of acrylic was installed with an air space between the top and bottom acrylic sheets, both being held in an extruded aluminum frame. Type BIIK is essentially a modification of Type BII in which a 0.125-in. tempered glass cover sheet is bonded over the top of the silicone encapsulant.

Note that Type BIIK, EI, and EII are the only designs tested that employ glass as part of the superstrate and/or encapsulant system. Types BIIK and EI are similar to the extent that they employ a glass superstrate in addition to an aluminum substrate. Type EII employs a 0.125-in. annealed glass superstrate as the sole means of cell support, although an aluminum frame and rubber gasket are employed to support the glass panel around its periphery.

HAIL IMPACT RESISTANCE OF PANELS

Table 3 summarizes the results of impacting molded ice spheres on the solar panels at velocities corresponding to the terminal velocities of naturally occurring hail. The heavy vertical lines in Table 3 demark the hail impact resistance of a given panel type. Examination of the table shows that the hail performance of solar panels is largely a function of the material used for the outermost layer. No panel design utilizing a clear silicone potting as the outermost layer proved capable of withstanding 1-in. diameter simulated hailstones without cell cracking. Two types using annealed glass as the outermost layer were capable of withstanding 1-in. diameter simulated hailstones, but the glass was broken under the impact of 1-1/4-in. diameter hailstones. Two other designs, one incorporating 0.10-in.-thick acrylic, the other 0.125-in.-thick tempered glass withstood 1-1/4-in., but not 1-1/2-in., diameter simulated hailstones.

Figure 4 shows the damage to a Type BII solar panel at the impact site of a 1.61-in. diameter molded ice sphere traveling at 70 mph. The damage shown is fairly typical of those module designs that employ a silicone rubber top surface encapsulant. The cell is extensively cracked, but even though the aluminum substrate is deformed, the silicone encapsulant is intact and adherent. Figure 5 shows the damage to a Type EII solar panel at the impact site of a 1.61-in. diameter simulated hailstone traveling at 70 mph. Again, this type of damage is typical of panel types incorporating annealed glass as the outermost surface (Types EI and EII). Note that the center of impact is near the edge of the panel. The glass panels were found to be much more prone to failure when impacted near the edge. The failure of type BIIK, which incorporates a tempered glass superstrate is very similar to the annealed glass types, except that

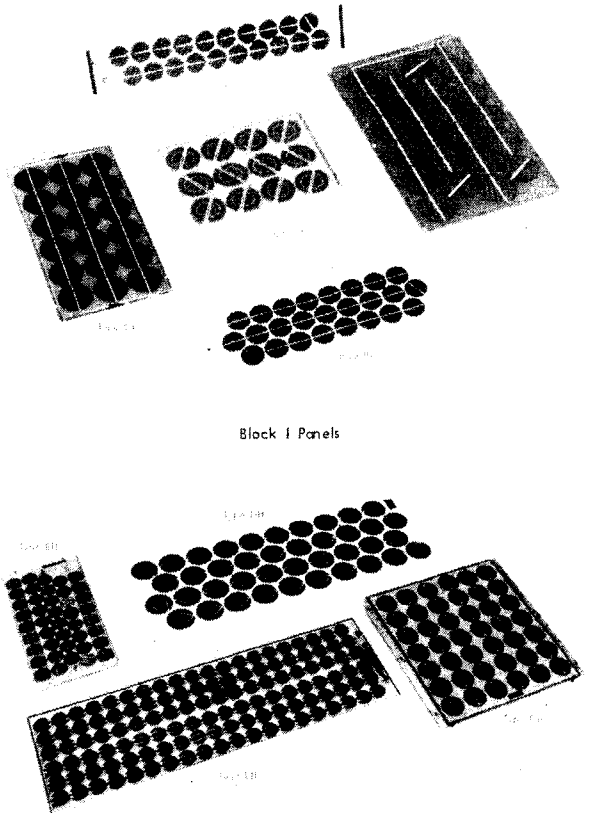


Fig. 3. Commercially available photovoltaic panels

the glass shatters over the entire surface of the panel.

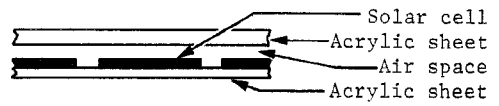
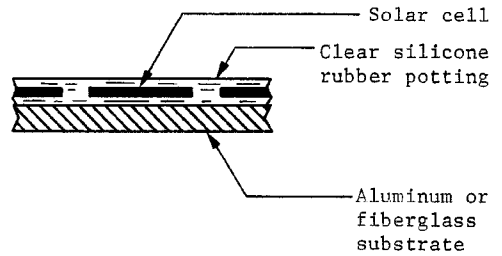
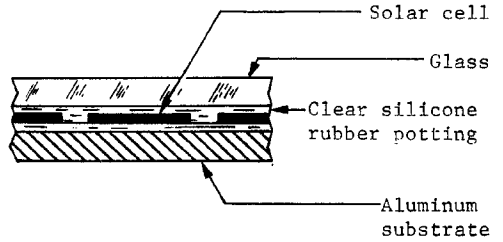
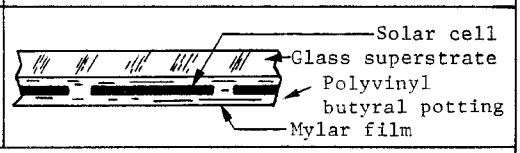
High-Speed Movies of Simulated Hailstone Impact

In an effort to better understand the failure mechanisms involved, high-speed motion pictures were made of ice balls impacting various panels. Using a Fastax camera and a frame rate of approximately 4500 per second, it was possible to study the ice ball fracture patterns at intervals of approximately 200 μs.

The camera used expended 100 ft of film at each operation, with useful data usually occupying about 10 ft of film. A total of 24 operations were made with three camera malfunctions. The useful film obtained was edited, titled, and stored on a single 400-ft reel to simplify handling and viewing.

Review of the data on this reel shows a great variety of failure mechanisms for the 21 ice-ball impacts recorded. In some cases, the ice ball merely bounced away from the panel it struck, in others it broke into a few large pieces after impact, and in others it broke into hundreds of small pieces. The frames of interest were enlarged and studied. Figure 6 shows the extremes of ice ball fractures observed.

Table 2. Mechanical design features of photovoltaic panels tested

Panel type	Overall dimensions, in.	Top surface material	Encapsulant	Substrate	Frame	Basic construction cross-sectional sketch
AI	16.3 × 12.9 × 0.8	0.10-in. acrylic sheet	None	0.10-in. acrylic sheet	Aluminum extrusion with rubber gasket	
BI	22.5 × 6.5 × 0.44	Silicone potting	Silicone potting	Aluminum extrusion integral stiffeners	None	
BII	22.9 × 11.4 × 1.8	Silicone potting	Silicone potting	Stamped aluminum pan integral stiffeners	None	
CI	20.0 × 10.3 × 0.19	Silicone potting	Silicone potting	Fiberglass sheet	None	
CII	22.9 × 22.9 × 1.8	Silicone potting	Silicone potting	Fiberglass sheet	Welded aluminum extrusions	
DI	24.0 × 14.8 × 0.25	Silicone potting	Silicone potting	Fiberglass sheet	None	
DII	46.0 × 15.3 × 1.9	Silicone potting	Silicone potting	Molded fiberglass integral stiffeners	None	
BIIK[a]	22.9 × 11.4 × 1.8	0.12-in. tempered glass	Silicone potting	Stamped aluminum pan integral stiffeners	None	
EI	26.1 × 4.9 × 2.7	0.09-in. annealed glass	Silicone potting	Aluminum extrusion integral stiffeners	None	
EII	46.0 × 15.3 × 1.4	0.12-in. annealed glass	Polyvinyl butyral and Mylar film	None	Aluminum extrusion with rubber gasket	

[a]Modification of Type BII.

Table 3. Observed damage to photovoltaic solar panels due to impact of simulated hailstones

Panel type	Top surface material	Test date	Hailstone diameter,[a] in., at velocity, mph					
			0.49 at 33	0.74 at 44	1.05 at 55	1.28 at 61	1.61 at 70	2.07 at 79
AI	Acrylic sheet	6/16/77			No damage	No damage	[b] Punctured top of acrylic sheet	
BI	Silicone potting	5/20/77		Slight cell cracking	Appreciable cell cracking	Extensive cell cracking	Extensive cell cracking	
BII	Silicone potting	4/28/77	Slight cell cracking 2 of 9 hits	Appreciable cell cracking	Extensive cell cracking	Extensive cell cracking; dents aluminum pan	Extensive cell cracking; dents aluminum pan	
CI	Silicone potting	6/14/77			Slight cell cracking, 1 of 4 hits	Appreciable cell cracking, 3 of 5 hits		
CII	Silicone potting	6/14/77		No damage	Slight cell cracking	Appreciable cell cracking	Extensive cell cracking	Extensive cell cracking; punctured fiberglass substrate
		9/28/77			Slight cell cracking	Appreciable cell cracking		
DI	Silicone potting	6/13/77		No damage	Slight cell cracking, 3 of 5 hits			
		9/26/77		No damage	Slight cell cracking			
DII	Silicone potting	4/27/77		Dents in silicone; slight cell cracking	Dents in silicone; appreciable cell cracking	Dents in silicone: extensive cell cracking	Dents in silicone; extensive cell cracking	Dents in silicone; extensive cell cracking; punctured fiberglass substrate
BIIK	Tempered glass	6/15/77			No damage	No damage	No damage: 2 hits; shattered glass: 1 hit near edge	
		12/20/77					No damage: 2 hits	No damage: 1 hit; shattered glass: 1 hit 3.5 in. from edge
EI	Annealed glass	6/14/77			No damage	No damage	Broke glass, 2 of 3 hits	
		6/17/77			No damage	Broke glass, 1 of 4 hits		
		9/27/77				No damage	Broke glass	
EII	Annealed glass	4/26/77		No damage	No damage	No damage: 2 hits middle; broke glass: 1 of 3 hits near edge	No damage: 3 hits middle; broke glass: 2 of 4 hits near edge	
		9/27/77				No damage	Broke glass	

[a]The diameters shown are the actual diameters of the simulated hailstones; nominal diameters are used elsewhere in this report.

[b]The heavy vertical lines indicate the approximate extent of the hail impact strength of a given design.

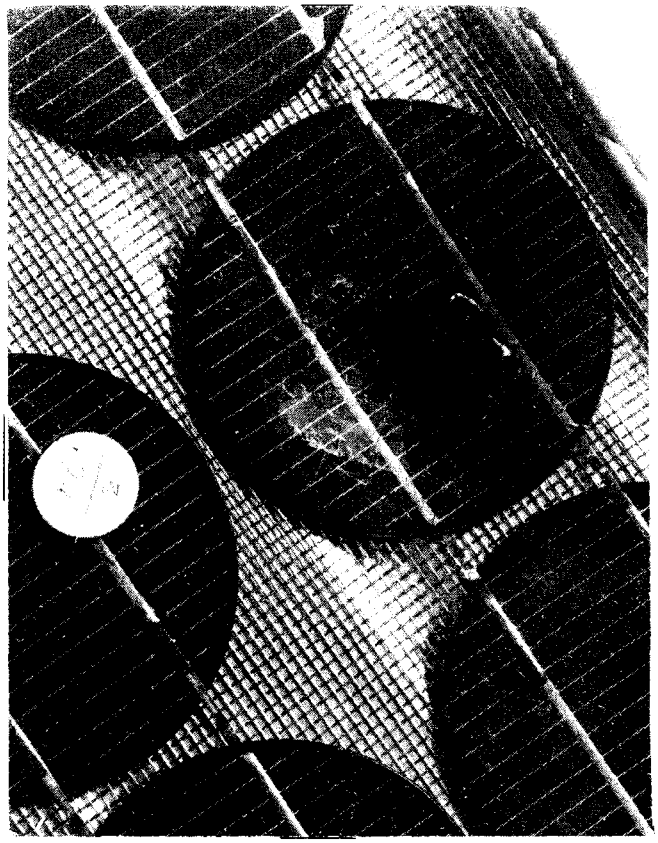


Fig. 4. Silicone rubber top surface (Panel Type BII) - impact site of 1.61-in. diameter/70 mph simulated hailstone

In one case, the ice ball bounced off a panel whose top surface layer was silicone rubber. In the second case, the simulated hailstone was shattered on impact with a glass panel. In only three of the 21 impacts filmed did the simulated hailstone remain intact; all three were 1.05-in. diameter simulated hailstones traveling at 55 mph that impacted panels whose top layer was silicone rubber. The fact that the ball bounced back is indicative of high peak force at the hailstone/panel interface. Analysis of the photographs of both bouncing and crushing balls indicates that the hailstone deceleration is complete approximately 0.001 s following impact. When the hailstone bounces, it is known that the entire ice ball decelerates simultaneously, and thus that the peak force reached was greater than with a crushed ball, where the deceleration gradually progressed from the leading surface to the ball rear.

The peak force generated is considered the critical parameter for those modules with silicone rubber front surfaces. With these modules, the cell is crushed between the hailstone and the module substrate that supports the cell. Cells were found to be particularly vulnerable when the substrate did not provide uniformly rigid support, as when voids or layers of silicone rubber greater than several thousandths of an inch thick existed below a cell. Design features resulting in this condition include:

(1) A corrogated substrate designed to enhance substrate bending stiffness, but leading to a grooved substrate surface.

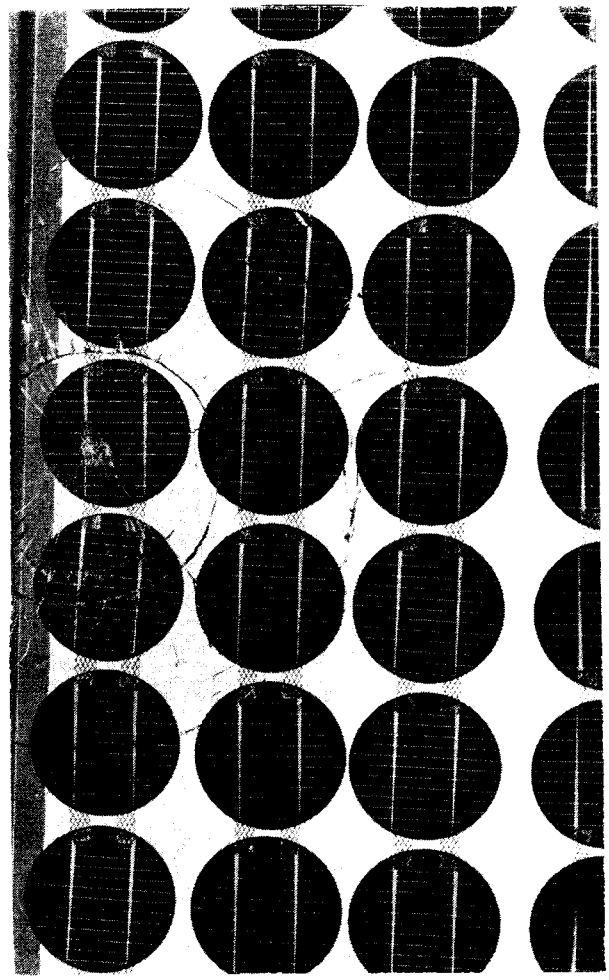


Fig. 5. Annealed glass top surface (Panel Type EII) - impact site of 1.61-in. diameter/70 mph simulated hailstone

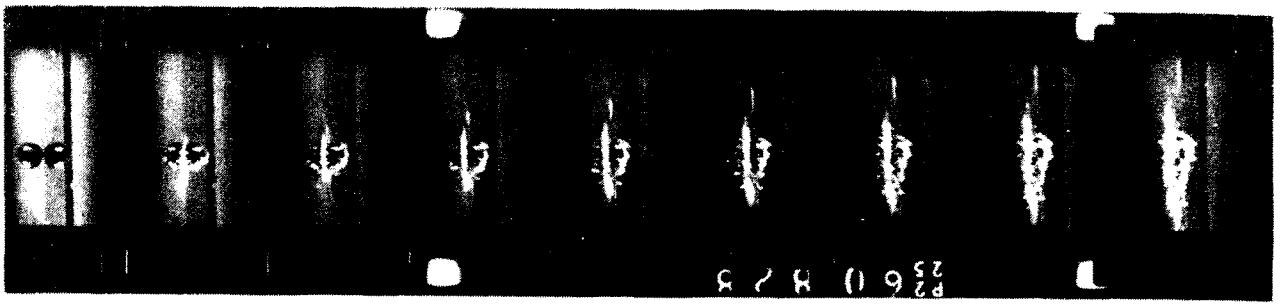
(2) Projections on the rear surface of the cells associated with the attachment of the rear electrical contacts or excessive solder buildup.

(3) Moderate layers of silicone rubber beneath the cell to provide electrical isolation and/or to provide for differential thermal expansion.

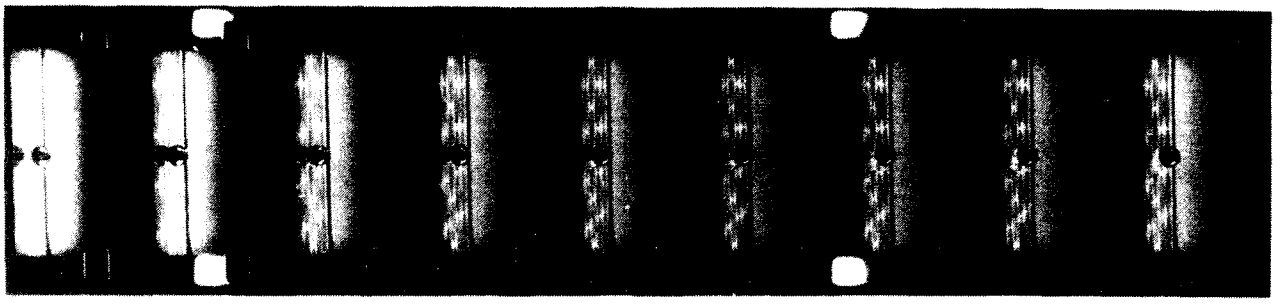
Unlike the silicone rubber panels, the glass in the glass panels is the critical element, not the solar cells. It has been determined that the failure is initiated within 200 μs of first contact (it occurs in the first movie frame showing impact). The failure mechanism has been identified as local plate bending where the crack initiates on the back side of the glass, as opposed to Hertzian cracks that initiate at the contact surface and form the characteristic conical fracture. As noted in Table 3, the use of tempered glass provided some improvement in impact strength.

Pre- and Posthail Electrical Power Measurements

In addition to the hail impact testing and the qualitative remarks recorded above pertaining to the



Impact on glass surface



Impact on silicone rubber surfaces

Fig. 6. Comparison of two types of impact behavior of 1.05-in. diameter/55 mph simulated hailstone

observed damage, quantitative electrical power measurements were made on four of the panel types before and after hail impact testing. In these tests, the electrical power output of the panel is measured while the panel is irradiated with a standard light source. The results of these tests appear in Table 4.

All four panel types were subjected to impacts by simulated hailstones ranging from a 3/4-to 1-1/2-in. diameter. In addition, Types CII and DII were impacted with 2-in. diameter ice spheres. Note further the number of hits per ft^2 of panel area was not held constant in these tests. Suffice it to say that not too much emphasis should be placed on the numerical values reported. These results do indicate, however, that the visual damage previously discussed has a marked effect on the electrical power output of the panels that employ a silicone rubber top surface. At the same time the power output of panel Type EII, which has an annealed glass top surface, is practically unaffected even though the glass is cracked as shown in Fig. 5.

SIMPLIFIED TEST METHODS

At the outset of the program it was recognized that the simulated hail impact testing method just discussed is rather elaborate and expensive. A simplified test method is desired. Having studied the failure modes of the panels subjected to simulated hailstone impact at some length, it was felt that the applicability of a simplified test method would be verified if that method reproduced (for all design types) the failure modes previously observed using simulated hailstones.

Dropped Steel Balls

The American National Standards Institute (ANSI) specifies dropped steel ball tests to determine the impact resistance of such items as safety glasses (Ref. 12) and motor vehicle safety glazing materials (Ref. 13). This type of test is simple and inexpensive and thus appeared to be a logical starting point. Table 5 summarizes the results of dropping steel balls on the various panel types. The critical drop

Table 4. Effect of hail impact on power output of photovoltaic panels

Panel	Hail impact test data	Total No. hits/ft^2 of panel area	Panel output power - P_{max}, W		Power degradation, %	Top surface material
			Prehail	Posthail		
BII	4/28/77	15	11.0	2.7	75	Silicone potting
CII	4/21/77	10	19.6	11.7	40	Silicone potting
DII	4/27/77	6	34.8	21.3	39	Silicone potting
EII	4/26/77	5	24.8	23.5	5	Annealed glass

Table 5. Critical drop height for steel balls

Panel type	Test date	Diameter of steel ball, in.		
		0.75	1.00	1.25
AI	6/27/77	>96	47	34
BI	6/27/77	27	10	12
CI	6/27/77	90	65	33
DI	6/27/77	>96	>96	90
DII	6/29/77	33	10	11
EI	6/27/77	17	16	12

height reported is the minimum drop height that produced failure of any kind (glass or cell fracture) when dropped on the most sensitive portion of the panel. The panels were supported as intended by the manufacturer.

In Fig. 7, the critical drop heights reported in Table 5 are plotted on the ordinate against the smallest simulated hailstone diameter reported to have caused damage (see Table 3).

Examination of this figure shows that there is very little correlation between steel ball drop tests and the impact strength of a photovoltaic panel subjected to impact by simulated hailstones. This is especially apparent for panel types CI and DI. The outermost layer of both is a clear silicone potting material, both have a critical simulated hailstone diameter of 1 in., yet the critical drop height for 1.25-in. diameter steel balls varies by a factor of nearly 4 to 1.

Also superposed on this figure are dotted and dot-dash lines that represent the steel ball drop height that will duplicate the kinetic energy and momentum, respectively, of a simulated hailstone of the same diameter. Note that the test results are approximately bounded by these two curves. Duplicating momentum yields reasonable correlation for three of the design types tested, but design types CI and DI correlate best with steel ball drop heights providing kinetic energy similitude. This lack of uniform correlation between dropped steel balls and simulated hailstones was considered sufficient to rule out further consideration of the dropped steel ball testing approach.

Statically Loaded Steel Balls

In the dropped steel ball tests, drop heights providing momentum similitude tended to produce the same damage as the simulated hailstone. This together with the fact that ice balls have a limited crushing strength encouraged the hypothesis that the damage might be related to the peak force applied by the hailstone. Figure 8 summarizes the results of applying static loads to a steel ball that was placed against the surface of the various panels. The panel was mounted as the manufacturer intended, and the steel ball was placed at critical locations on the panel surface (near the edge of glass panels and near the edges of cells at cell junctions for silicone encapsulated panels). The minimum static load that produced failure of any sort is plotted against the minimum diameter of simulated hailstone diameter to have caused like damage.

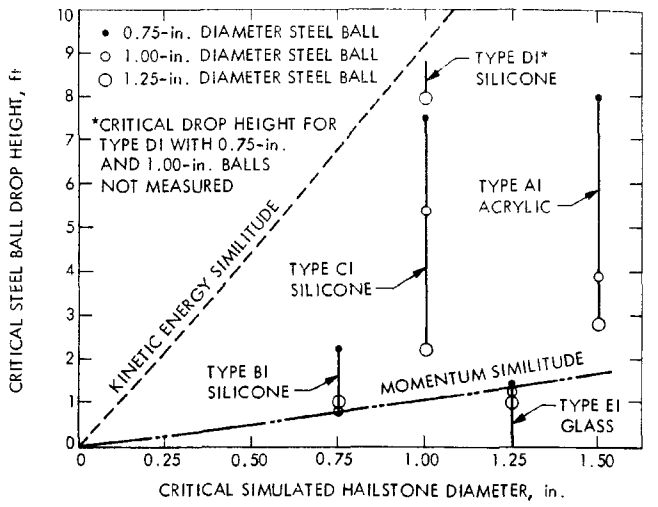


Fig. 7. Correlation of damage due to dropped steel balls with damage induced by simulated hailstones

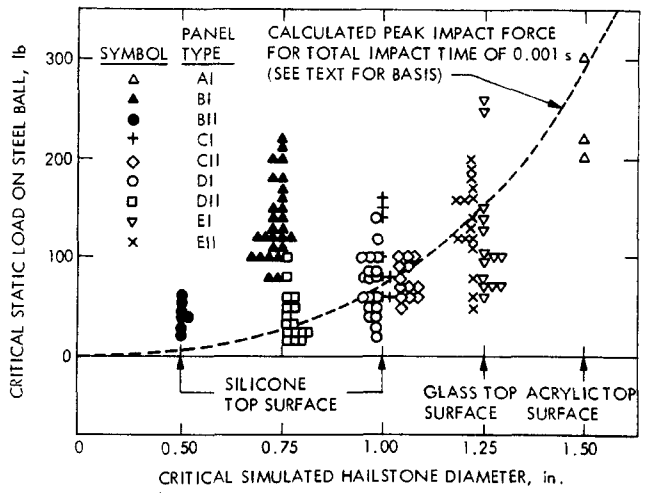


Fig. 8. Correlation of damage due to statically loaded steel balls with damage induced by simulated hailstones

The scatter in the data is indicative of the brittle nature of the materials being tested. The silicon solar cells that fail on those panels employing a clear silicone rubber top surface and the glass that fails on those designs employing glass cover sheets are both brittle materials.

Superposed on the test results is a dotted curve representing the calculated value of the peak impact force based on the following considerations. The impulse or momentum change of the simulated hailstone is given by

$$\int F dt = m\Delta v \qquad (2)$$

where F is the impact force, t is the time, m is the mass of the simulated hailstone, and Δv is the velocity change undergone by the hailstone during impact. If the force-time history of impact is assumed to be a half-sine pulse, Eq. (2) becomes

$$F_{peak} = \frac{\pi}{2} \frac{m\Delta v}{t_i} \quad (3)$$

where t_i is the total impact time. The dotted curve shown in Fig. 8 is based on a total impact time of 0.001 s and a hailstone rebound belocity of 10% of the approach velocity so that $\Delta v = 1.1$ v. Both of these values were observed in the analysis of the high-speed movies taken of simulated hailstone impact on photovoltaic solar panels. These comments are primarily of academic interest, but it is interesting to note that the general trend of the data follows this analytical model.

Except for the poor correlation of panel type BI, statically loaded steel balls might be considered as a simple means of assessing the hail impact strength of photovoltaic solar panels.

IMPROVING PANEL IMPACT STRENGTH

The tests already discussed were directed toward assessing the hail impact resistance of current commercially available solar panels. The additional tests and considerations discussed here are intended to provide ground work for improving the impact resistance of future generations of photovoltaic solar panels.

Edge Effects — Glass Panels

During the testing conducted to assess the hail impact resistance of the commercially available solar panels, it was noted that those designs employing glass were much more subject to damage when struck near the edge of the glass panels.

This effect was further studied by making up a series of dummy solar panels by installing double strength window glass 45 in. × 15 in. × 0.125 in. in an aluminum frame with a rubber glazing gasket. A cross section near the frame edge is shown in Fig. 9. This configuration very nearly duplicates the configuration of panel type EII.

These test panels were tested with double strength window glass (annealed glass, 0.12 in. thick) having both ground and unground edges. Dropped and statically loaded steel ball tests were performed. The results of the drop tests are summarized in Table 6.

These tests show that there is little improvement to be gained in the impact resistance of glass panels by increasing the edge distance from 0.75 in. to 2.5 in. It would not, therefore, be practical to improve the impact resistance by protecting the glass panel edges with wide aluminum frames, for example. There is, however, substantial improvement to be gained by grinding the edges of glass panels, or otherwise improving the finish of same.

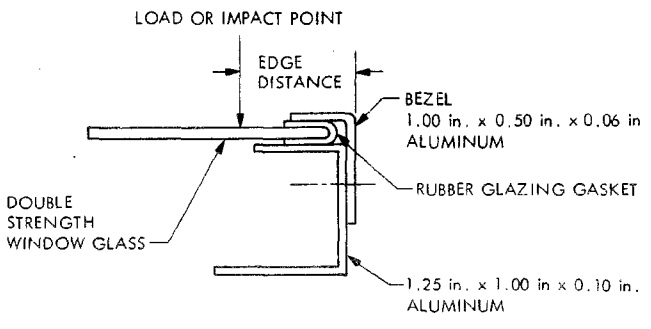


Fig. 9. Edge configuration-edge effect test panel

Evaluation of Candidate Top Layer Materials

It has been shown that the top layer of the solar panel is of paramount importance in determining the impact strength of solar panels. The outermost layer of a photovoltaic solar panel that protects the silicon solar cells from the environment should be low-cost, transparent, weather and abrasion resistant, and should have good impact resistance. Additional testing was performed on acrylic sheets to determine whether a panel could be constructed to survive the impact of a 2-in. diameter hailstone. The results of these and previous tests are shown in Table 7 along with data on cost, transparency, weather and abrasion resistance. Annealed glass has the advantage in all categories, especially cost, except for resistance to hail impact. Acrylic panels could be made to withstand 2-in. diameter hailstones.

CONCLUSIONS

Based on the work reported herein, a number of useful general conclusions may be drawn.

(1) None of the six panel designs incorporating clear potting silicone material as the outermost layer was capable of protecting the silicon solar cells from damage due to impacts by simulated hailstones of 1-in. diameter or larger.

(2) The two module designs using annealed glass as the outermost layer could withstand the impact of 1-in. diameter, but not 1-1/4 in. diameter simulated hailstones.

(3) The module designs using 0.100-in. thick acrylic and 0.125-in. thick tempered glass could withstand the impact of 1-1/4-in. diameter, but not 1-1/2-in. diameter simulated hailstones.

(4) The simplified test methods evaluated, namely, the dropped or statically loaded

Table 6. Critical steel ball drop height for glass panels with various edge conditions

Steel ball diameter, in.	Critical drop height, in.			
	Unground edges		Ground edges	
	0.75-in. edge distance	2.5-in. edge distance	0.75-in. edge distance	1.5-in. edge distance
0.75	40	44		
1.00	28	35	54	54
1.25	22	44		

Table 7. Evaluation of candidate solar panel top surface materials

Material	Thickness, in.	Critical simulated hailstone diameter, in.	Cost, $/ft^2	Transparency	Weather resistance	Abrasion resistance
Annealed glass	0.125	1.00	0.3	Excellent	Excellent	Excellent
Tempered glass	0.125	1.25	1.0	Excellent	Excellent	Excellent
Acrylic	0.100	1.25	0.8	Excellent	Very good	Good
Acrylic	0.125	1.50	0.9	Excellent	Very good	Good
Acrylic	0.188	2.00	1.0	Excellent	Very good	Good

steel ball tests, did not provide acceptable correlation with the simulated hail impact tests.

(5) A photovoltaic module employing a 0.188-in. thick acrylic cover sheet would be capable of withstanding the impact of a 2-in. diameter hailstone.

RECOMMENDATIONS

This program has provided much useful information with regard to the hail impact strength of current photovoltaic solar panels, design features that enhance or detract from that strength, and has produced some information pertinent to the problem of finding a simpler test method to evaluate the hail resistance of solar panels. At the same time, it has emphasized the need for further study in the following areas:

(1) Study the direction and magnitude of the winds that accompany hailstorms to better assess the angle of incidence of the hailstone impact on photovoltaic solar panels.

(2) Subject panels to oblique hailstone impact at probable angles of incidence to see how this affects the hail resistance of the panels.

(3) Explore the life-cycle cost effectiveness of various degrees of hail resistance.

(4) Examine the validity of using ice spheres or other means to simulate impact by naturally occurring hailstones.

(5) Further study of a simpler test method to evaluate hail impact resistance of solar panels.

(6) In addition, those design features of solar panels that most influence the impact strength should be studied further to find cost effective means of enhancing the hail impact resistance of photovoltaic solar panels. Fire polishing the edge of glass panels, for example, should be studied.

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