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**NEED FOR AND EVALUATION OF HAIL PROTECTION
DEVICES FOR SOLAR FLAT PLATE COLLECTORS**

Final Report for June 1978—March 1980

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1. INTRODUCTION

This report documents work that has been performed by Altas Corporation under contract to the U.S. Department of Energy. The purpose of this contract has been the evaluation of "Cost Effective Hail Protection Devices for Solar Flat Plate Collectors."

The context of this work must be noted at the outset. First, flat plate collectors are not the only solar installations susceptible to hail breakage. In fact, other installations, such as parabolic reflectors [2] and photovoltaic arrays [3] appear more susceptible. Research to protect solar equipment from hail is underway at a number of institutions. At least three groups are currently developing standards for solar equipment to withstand hail impact (the Department of Energy in conjunction with national code organizations [14], the American Society for Testing Materials [12], and Underwriters' Laboratories). The present contract should be viewed in this broader context.

Many approaches could be taken to develop "cost-effective hail protection devices" for any ground installation. Altas's approach has been:

- 1) to determine the "maximum probable hailstone size" that will strike a given area in a given locale in a given time period.
- 2) to evaluate the resistance of solar installations to impact by such hailstones.
- 3) to evaluate possible protection devices and...
- 4) the economic feasibility of those devices.

This research structure is consistent with work performed elsewhere.

A second point should be noted at the outset. Clearly, the glazing on a flat plate collector is the component most susceptible to hail damage. Three approaches to protect the glazing are immediately apparent: 1) integrate the protection into the glazing (e.g., choose a material strong enough to withstand the "maximum probable hailstone size" in the lifetime of the collector), or 2) develop an external

protection device to withstand such a hailstone (e.g., suspend a screen above the glazing), or 3) design for easy replacement of the glazing. The first two approaches are discussed in this report. Trade-offs must be made in all three cases. The cost trade-offs associated with the third approach, while beyond the scope of this contract, bear further investigation. In Section 5.B. it is shown that the cost (in lost collector efficiency) of the use of cover screens is most likely prohibitive.

Impact resistance is not the only basis on which to choose a glazing material. One must consider transmissivity, the temperature range of the collector, cost, and the glazing's susceptibility to thermal stress, thermal degradation, UV degradation, etc. (See Ref. [8] for a good discussion of commercially available glazing materials. Also, Ref. [15] discusses silicones as compared with glass for use in flat plate collectors.)

A rigorous cost-benefit analysis would consider these factors in addition to the particular application of the collector. Such an analysis was beyond the scope of the present contract. Note that for the purposes of this contract, the maximum probable hailstone size has been used as an index of hail damage risk in a given location. This is the maximum hailstone size predicted with a "ultimate risk" of .50 (see Ref. [1]). The maximum probable hailstone size is the "average" level of risk on which one can base comparisons among different hail protection strategies. If a particular glazing material withstands impact by the maximum probable hailstone size for a given installation, that material can be judged as a viable glazing for flat plate collectors in that installation. Some glazing materials will not withstand impact of the maximum probable hailstone size in any area of the "hail belt". Should these glazings be used, hail protection will be necessary. If screens are used, the benefits of the glazings will have to outweigh the costs noted in Section 5.B.

Section 2 of this report provides a brief summary of the hail risk work done under this contract and already documented in great detail in a previous technical report (Ref. [1]). Section 3 is a summary evaluation of hail impact resistance standards currently being developed. Section 4 discusses "simulated hail impact test" data, field data, and the impact resistance of commercially available glazings. In Section 5, the use of screens for protection against hail is discussed. The threat of vandalism to solar flat plate collectors is discussed in Section 6.

2. INCIDENCE OF DAMAGING HAIL

It became clear at an early stage in this contract that insufficient work had been done to determine the incidence of potentially damaging hail.

One factor in the cost of collecting solar energy is the cost of maintaining solar collectors. A potentially significant component of this maintenance cost is the cost of repairing hail damaged collectors. It is important to be able to estimate the incidence of damaging hail so that the cost of solar power can be compared with other power sources on an equitable basis, and so that hail resistant collector designs can be optimized for different hail prone regions.

An assessment of the incidence of damaging hail, which is an essential complement to impact testing carried out to determine damage thresholds of solar materials, has been a major focus of the present contract.

Altas' work in this area has already been described in detail in a previous technical publication [1], but briefly:

A statistical model has been developed for estimating the risk of impacts by large hail on any ground installation (such as a solar collector array). The model is based on data for three frequency distributions: hailstone size, hailfall count (number of hailstones per m^2 per storm), and number of haildays per year. Other than parameters derived from meteorological data, the parameters of the model required to describe a particular installation are the number of years of surface exposure and the area of the exposed surface. The independent variable is the critical hailstone diameter, D . The result given by the model is the probability of a hailstone of diameter D or greater striking a given surface area in a given number of years. Thus it is possible to determine the "probable maximum hailstone size", and convenient index of hail risk. Alternatively, the "mean time between hits" may be computed for a given size of hailstone. This model improves on previous work in describing all three of the distributions needed to characterize the variability of large hail incidence: hailstone size, count, and storm frequency, and in identifying better analytical expressions for these distributions: a special beta function

for hailstone size, a gamma function for hailfall count, and a Poisson function or a negative binomial function for annual hailday frequency. The independence of these three random variables is also discussed.

Conclusions from Ref. [1] are cited in the present report, and for convenience, summary information is provided in Table I, and Figures 1 and 2.

The "maximum probable hailstone size" is listed for four locations in Table I. 'A' is the collector area, 'K' is its expected lifetime. There are a few basic hailstorm types. The three size distributions used in Table I are based on data gathered in different types, and each also represents a different approach to extrapolating the raw data to larger hailstone sizes. This is discussed in Ref. [1]. Briefly, we believe the most accurate prediction of the "maximum probable hailstone size" for any combination of A and K lies somewhere between the figures calculated using the Colorado and Alberta size distributions, and probably closer to the figure calculated using the Colorado size distribution.

Figure 1 shows hailstone terminal velocity vs. size, Figure 2, hailstone terminal kinetic energy vs. size.

		Size distribution used	Surface area exposed, A m ²	Number of years of exposure (K)				
				5	10	20	50	100
Albuquerque, New Mexico	COLORADO	10		2.95	3.12	3.17	3.35	3.48
		50		3.2	3.4	3.5	3.58	3.7
		100		3.4	3.5	3.55	3.75	3.8
	ALBERTA	10		4.05	4.25	4.35	4.75	4.95
		50		4.4	4.8	5.0	4.15	5.47
		100		4.8	5.0	5.15	5.5	5.7
	ILLINOIS	10		4.45	4.6	4.7	5.05	5.25
		50		4.75	5.15	5.35	5.45	5.7
		100		5.15	5.35	5.4	5.75	5.95
Abilene, Texas	COLORADO	10		3.1	3.14	3.25	3.4	3.5
		50		3.35	3.47	3.55	3.63	3.75
		100		3.48	3.54	3.63	3.78	3.83
	ALBERTA	10		4.23	4.34	4.46	4.83	5.0
		50		4.72	4.95	5.06	4.2	5.5
		100		4.96	5.10	5.2	5.6	5.75
	ILLINOIS	10		4.58	4.7	4.8	5.15	5.3
		50		5.05	5.3	5.4	5.5	5.8
		100		5.3	5.4	5.5	5.83	6.0
Kansas City, Missouri	COLORADO	10		3.15	3.17	3.3	3.45	3.55
		50		3.4	3.5	3.6	3.7	3.8
		100		3.5	3.57	3.66	3.81	3.85
	ALBERTA	10		4.28	4.37	4.6	4.9	5.05
		50		4.83	5.0	5.12	5.33	5.6
		100		5.05	5.15	5.3	5.7	5.77
	ILLINOIS	10		5.63	4.72	4.92	5.21	5.32
		50		5.15	5.35	5.5	5.6	5.85
		100		5.35	5.45	5.6	5.9	6.05
Cheyenne, Wyoming	COLORADO	10		3.25	3.5	3.82	3.92	4.2
		50		3.55	3.73	4.08	4.2	4.45
		100		3.63	3.82	4.2	4.25	4.53
	ALBERTA	10		4.45	4.95	5.7	5.8	6.45
		50		5.05	5.5	6.25	6.45	6.97
		100		5.2	5.7	6.45	6.57	7.15
	ILLINOIS	10		4.8	5.27	5.95	6.08	5.95
		50		5.4	5.7	6.45	6.6	7.15
		100		5.5	5.95	6.63	6.75	7.3

Table I. Probable maximum hailstone size (ultimate risk = .50) as predicted by the risk model of Ref. [1]. Numbers shown are hailstone diameters in centimeters.

Figure 1. Hailstone terminal velocity vs. size, for three elevations

Figure 2. Hailstone terminal kinetic energy vs. size, for three elevations

3. DEVELOPMENT OF HAIL IMPACT RESISTANCE STANDARDS

Two criteria can be used to evaluate impact resistance standards for solar collectors to withstand hail:

- 1) Do the standards require a collector to withstand a hailstone size (or impact energy) that is likely to occur?
- 2) Do the tests realistically appraise the impact of such a hailstone?

Based on the work performed under the present contract with the Department of Energy (and primarily that work documented in Ref. [1]) Altas offers comments on the standards currently under development. Perhaps the most far-reaching standards currently underway are being developed by the U.S. Department of Energy in conjunction with code organizations such as the Council of American Building Officials. These standards are contained in the "Proposed Document for Code officials on Solar Heating and Cooling of Buildings" [14]. Section B.108.2c of the Second Draft outlines requirements for solar collectors to withstand hail.

These requirements are seriously inconsistent with the hail incidence estimates developed in [1]. The full text of our comments on the "Proposed Document" submitted to Mr. B.S. Trant of The Council of American Building Officials is reproduced in Appendix A of the present report. Briefly, however, our objection to Section B.108.2c of Ref. [14] is in regard to the requirement for a collector to withstand impact by a hailstone whose diameter is:

$$D = 0.3 d$$

where

d = the mean annual number of haildays at a particular locale.

D is in inches.

It is unknown to us how the expression $D = 0.3 d$ has been derived, and upon which hail data it has been based, but this expression is entirely inconsistent with our results. D , which we have referred to as the

"maximum probable hailstone diameter" in Ref. [1], is not simply a function of the mean annual number of haildays, d , in a particular location. Concerning only the hailday distribution, Atlas has shown that the variance of the distribution is of roughly the same significance in determining D as is d , the mean. Furthermore, D is dependent on the collector area and lifetime of the collector, which are not included as parameters in the algorithm in the "Proposed Document".

Our results show that even for fairly large collector sizes and installation lifetimes (e.g. $A = 50 \text{ m}^2$, $K = 20$ years) the expression $D = 0.3 d$ overestimates the hail risk for most "hail belt" areas. For example, in Cheyenne, Wyoming, this algorithm would require a collector to withstand impact by a 3 inch hailstone. The results from the hail risk model of Ref. [1] predict only a 1.6 inch hailstone for the collector size and lifetime noted above.

The American Society for Testing Materials (ASTM) Committee E-44 on Solar Energy Conversion is currently writing hail standards. The standards, however, do not specify criteria for performance (i.e., specifying what hailstone size collectors must withstand) but rather outline a procedure for testing [10,12]. The biases of this test procedure are discussed in the ASTM standards and also in Section 4.B of the present report. Briefly, however, the major unanswered question is whether impact by an ice sphere accurately represents impact by the same size (or weight) hailstone.

4. HAILSTONE IMPACT RESISTANCE OF SOLAR INSTALLATIONS

4.A. Field Data

Two severe hailstorms have recently occurred from which data on hail damage to solar installations were gathered.

Fort Collins, Colorado

During the summer of 1979 a severe hailstorm, with a hailswath two to four miles wide [7], passed through Fort Collins, Colorado. The average hailstone diameter was greater than one inch and the maximum stone diameter was greater than four inches [7].

Eleven solar installations were in the storm's path, with a total area of $\sim 11,000 \text{ ft}^2$ exposed to the storm. All of these collectors had glass cover plates; all but a few of the panels in the path of the storm were glazed with $1/8$ inch tempered glass.

Also in the path of the storm were a number of greenhouses which were glazed with both single strength unttempered glass and fiberglass reinforced polyester (FRP).

The number of glass panels broken on solar collectors was less than 1 percent of the total number of panels in the path of the storm. The FRP glazing on greenhouses was considered "visually acceptable", but it was considered necessary to replace it "because of small fractures and perforations at points of hail impact" [7].

Ref. [7] concludes that:

- 1) the threat of hail damage to collectors glazed with $1/8$ inch tempered glass is negligibly small
- 2) The breakage rate for $1/8$ inch tempered glass can be expected to be no greater than 5 percent for hailstones of 3 to 4 inches in diameter
- 3) Fiberglass reinforced polyester (FRP) sheets used as glazings appear to be less resistant to hail damage than $1/8$ inch tempered glass.

It should be noted that collectors in the path of the Ft. Collins storm faced south at slopes between 32 and 56 degrees; most of the installations and 80 percent of the exposed collector surface faced south at a slope of 45 degrees.

The hailstorm traveled through Ft. Collins in a southeasterly direction, i.e. from the backside of the collector.

The first two conclusions from Ref.[7] noted above are premature. No evidence is provided in Ref. [7] that the largest hailstones, 3 to 4 inches in diameter, struck any of the collectors in the hailstorm's path. It should be noted that the spatial distribution of such hailstones, even in such a severe storm as that in Fort Collins, is very small. The fact that these hailstones were observed does not mean they were predominant, or that they struck the relatively small target area of collector surface on the ground. It should be noted that the 50 percent breakage threshold of 1/8 inch tempered glass (discussed in Section 4.C.) is found for smaller than a 2 inch hailstone.

The third conclusion from Ref.[7] noted above is borne out by the experimental data, discussed below.

Albuquerque, New Mexico

In the late summer of 1979, a "severe" hailstorm passed through Albuquerque, New Mexico, striking Sandia Laboratories' solar systems test facility. Although flat plate collectors were not at the facility, there were other vulnerable devices, such as parabolic reflectors, fixed mirror collectors, and photovoltaic arrays. Most hail in this storm fell from the west and the south. In spite of this, very little damage was observed (see Ref. [17] for further details).

The hailstorm was noted as the "most severe in Albuquerque in the last five years" [17]. Hailstone sizes reportedly ranged from 12 to 19 mm (1/2 to 3/4 inch). Hailfall density was extreme, judging from reports of hail drifts of up to 20 cm deep the morning after the storm, 10 to 12 hours later. However, an error has been made in labeling the Albuquerque storm "severe" with respect to damage to man-made structures. With respect to crop damage, on the other hand, the storm can be considered severe.

Two important distributions used to characterize hailstorms are the

hailstone size distribution, and the hailfall density distribution. The latter is typically characterized by the total number of hailstones that fall per storm, n , vs. the number of occurrences. The hailstone size range reported for the Albuquerque storm was an average range for storms anywhere in the "hail belt". In fact, the maximum hailstone size predicted to strike any given 10 m^2 surface in Albuquerque in 5 years is about 3 cm [1], significantly larger than the maximum size reported in the Albuquerque storm. The Albuquerque storm was, on the other hand, on the tails of the hailfall density distribution. In very few storms does so much hail fall.

Crops damage is primarily a function of the density of hailfall. For this reason, the Albuquerque storm was severe with regard to crops. Damage to man-made structures, on the other hand, is primarily a function of the hailstone size distribution, and as demonstrated in the Albuquerque storm, is rather insensitive to the density of hailfall.

The minimal damage observed is consistent with simulated hail impact test data available [2,3,4,5]. The maximum wind velocity was reportedly 50 km/h [17]. Assuming that the wind forced hailstone impact on all installations to be normal, the terminal velocity, V_T , of hail was

$$V_T = V_H + 50 \text{ km/h.}$$

where

V_H = the hailstone terminal velocity in freefall.

Even for a 2.5 cm hailstone at the velocity V_T above, simulated hail impact testing [2,3,4,5] has shown very little damage to the types of solar installations cited in Ref. [17], quite consistent with the field observations.

Finally, it was noted after the Albuquerque hailstorm that "polymer-type insulation materials that had been exposed to weather for 2 years or longer suffered more severe damage than did those exposed for shorter periods" [17].

4.B. Simulated Hail Impact Testing

Researchers at a number of institutions have conducted or are currently conducting simulated hail impact testing on solar equipment [2,3,4,5,11,16]. This is presumably patterned after the bird impact testing conducted on airplane equipment [13,6]. The American Society for Testing Materials (ASTM) draft "Standard Practice" [12] is the basic test procedure currently used for hail impact testing. In this test, simple ice balls (corresponding in size to natural hailstones) are propelled at the test specimen at the terminal velocity of the corresponding natural hailstone. A series of ice spheres is fired at the test specimen at normal incidence. The smallest ball is fired first, and the diameter increased until breakage occurs.

In the case of solar flat plate collectors, full-sized collector glazing panels are generally used. These are mounted in rigid frames with the edges, as in a real collector, cushioned by neoprene gaskets.

There is some variation in this test procedure from lab to lab. There appears to be general agreement that corner impacts are the most critical [5,6,10]. Ref. [12] recommends impact 8-1/2 inch diagonally from the corner. Previous work with bird impact testing has also shown that corner impacts are the worst case and that 2 ft. x 2 ft. panels thus suffice [6]. Atlas has based its test procedure on this data, and impact testing was conducted on 2 ft. x 2 ft. panels of test material.

Atlas deviated from previous impact testing in the hail gun design. A crossbow was used rather than an air gun (which is most widely used) or a slingshot [4]. The design of the crossbow is documented in the following section.

The limitations of the current simulated hail impact testing (including Atlas's) should be noted: "No direct relationship has been established between the effect of impact of artificial and natural hailstones in relation to their physical properties. It is judged that owing to the greater density of ice balls, any discrepancy between the effects of artificial and natural hailstones at a given velocity will have a conservative bias" [12]. In addition, natural hailstones are formed by the accretion of layers (often alternating between water and ice), while ice spheres used in testing are solid. It is quite probable that real hailstones are softer than artificial hailstones, thus crushing more readily on impact and transferring less energy than the same size

ice sphere to the impact target. Again, this introduces a conservative bias into the results.

There are, therefore, at least four possible sources of conservative bias in the results of current impact testing: 1) Ice spheres are at the upper limit of the range of hailstone densities, thus generally heavier per unit size, thus impact energy of ice spheres is greater; 2) ice spheres are probably less compressible than hailstones, thus more energy is dissipated in the ice sphere's destruction and less energy imparted to the target on impact; 3) ice spheres are impacted on corners of test specimens in almost all tests, where the damage threshold is lower; 4) angle of incidence is normal to the test specimen.

It is interesting to note findings made by Mr. Milton Smith, who conducted simulated hail impact testing using ice spheres made from carbonated water. The resulting ice spheres were less dense than normal ice spheres and caused considerably less damage to the test specimens [5].

One last point needs attention. Most hailstorms are accompanied by strong winds. Many researchers have accounted for the potential added velocity to the hailstone's freefall velocity with:

$$V_T = (V_H^2 + V_W^2)^{1/2} \quad (4.1)$$

where

V_T = the resultant hailstone terminal velocity.

V_H = hailstone freefall velocity.

V_W = wind velocity.

The effect of wind in hailstorms is not evaluated in the present report.

4.C. Altas Hail Gun Design

Compressed air guns [2,3,11] and slingshots [4] have been used to propel ice balls in past hail testing work. With air guns the muzzle must be changed to accept different sized ice balls. Also a large air compressor and a special quick acting valve are required. Even with careful design, difficulties (such as the breaking up of large ice balls in the muzzle) have been encountered [2,3]. Slingshots, on the other hand, are generally restricted to the low terminal kinetic energies of smaller hailstones ($D < 3$ cm corresponding to $E_k \approx 2$ Joule); however, the slingshot is capable of propelling a series of ice balls of approximately equal mass with very repeatable velocities (standard deviation less than 2 percent of mean velocity [4]).

In view of these past experiences, a hail gun design modeled after a crossbow appeared to offer both repeatability and high kinetic energies in a reasonably low cost device. These goals were eventually achieved but only after several design and prototype iterations. The final working design is illustrated in Figure 3. To facilitate others in reproducing (or scaling up or down) this hail gun, the basic approach and salient details of the design are summarized below.

The crossbow is essentially two elastic cantilever beams. As the bow string is pulled the beams are deflected and the work of pulling the bow string is transformed into potential energy stored in the beams. Two factors must be considered in designing the beams. First, the amount of potential energy which can be stored in a stressed beam is limited by the stress at which the beam material deforms inelastically. Second, in this application it is important to minimize the mass of beam required to store a given potential energy. For any homogeneous, rectangular cross section, cantilever beam loaded at its free end, the lowest mass (or volume) is achieved by a cross section which varies along the length of the beam. The cross section must vary in a manner such that the second area moment about the bending axis decreases uniformly from the fixed end of the beam to zero at the free end. (Of course, this tapering will have to be discontinued at a distance from the free end where the cross sectional area is just sufficient to withstand the shear stress developed at maximum deflection.)

The familiar leaf spring approximates this tapered geometry and the slightly modified "quarter elliptical" automotive leaf springs used in the Altas hail gun are plainly evident in the photograph. The maximum

Figure 3. Altas hail gun.

potential energy one can theoretically store in such a spring is given by

$$E_{\text{pmax}} = \frac{V \sigma_e}{12 Y} \quad (4.2)$$

where Y , the modulus of elasticity [Nm^{-2}], and σ_e , the yield stress [Nm^{-2}], are physical properties of the spring material and V is the volume of the beam [m^3].

Although the volume of a particular beam material is determined by the potential energy required to launch a large hailstone, equation (4.2) gives no clue as to whether the leaf spring should be short and stout or long and slender. In the extremes, a long beam will be unwieldy and inclined to buckle while a short beam will subject the ice ball to an overly intense, possibly damaging acceleration. A leaf spring is quite flexible in this regard because various numbers of leaves of various lengths may be cut from the same spring stock to assemble a wide range of leaf spring geometries. From the leaves of a salvaged automotive spring, for example, one can assemble a compliant 1.5 m 3-leaf spring or a stiff .5 m 9-leaf spring. Table II gives the leaf spring dimensions along with other pertinent dimensions of the Altas hail gun.

The two springs together have a volume of $.0020 \text{ m}^3$ of which about 30 percent is not stressed effectively or not stressed at all (e.g., 12 cm of the thick end are clamped rigid). Assuming $\sigma_e = 7 \times 10^8 \text{ Nm}^{-2}$ (105 psi) and $Y = 2 \times 10^{11} \text{ Nm}^{-2}$ (2.9×10^7 psi) the two springs can store 410 Joules.

The static force-deflection response of the bow string is shown in Figure 4. Because the failure of a spring would be dangerous to personnel, considerable caution was exercised in never drawing the bow to more than 200 J (less than half of the estimated theoretical maximum). Moreover, not all of the energy stored in the cocked crossbow is imparted to the ice ball. Most of the potential energy is expended accelerating the launch carriage, bow string and leaf spring, all of which are in motion when the projectile is released. A maximum projectile kinetic energy of about 90 J was obtained. This represents 45 percent of the measured energy stored in the bow at the self-imposed maximum bow string deflection or 22 percent of the estimated energy storable if the bow were stressed to its yield point.

After the projectile is released the launch carriage must be brought to rest in a very short distance. To accomplish this, the launch carriage is provided with an automatic braking mechanism whereby the track rails

Table II. Hail Gun Dimensions

bowspan	1.74 m	(68.5 in)
spring material	spring steel (automotive leaf spring)	
number of leaves	5	
overall length	.89 m	(35 in)
clamped length	.127 m	(5 in)
base to bow string eye	.76 m	(30 in)
leaf thickness	6.15 m	(0.242 in)
leaf width	62.2 m	(2.45 in)
total volume (pair)	.00200 m ³	(121.8 in ³)
estimated effective volume (pair)	.00137 m ³	(83.4 in ³)
bow string material	aircraft cable	
bow string diameter	3.96 mm	(0.156 in)
carriage material	6.35 mm	(1/4") aluminum
carriage guide material	steel drill rod	
front guide rod diameter	7.94 mm	(.3125 in)
rear guide rod diameter	9.52 mm	(.375 in)
total carriage mass	.382 kg	(.842 lbm)
max nominal projectile diameter	9 cm	(3.5 in)
track length	1.5 m	(60 in)
frame material	38x38 mm	(1.5x1.5 in) angle iron

Figure 4. Force-deflection curve of cantilever beam.

pinch the carriage guide rods when the carriage reaches the projectile release point. This was done by having the lower rails, a, fixed and the upper rails, b, hinged at the back of the gun, c, as shown in Figure 5. The rail separation is adjusted at the front of the gun, d, so that the guide post clearance decreases from back to front and is zero at the release point, e. (In the Atlas hailgun, the rail separation decreases by only about 1 mm over the 1.5 m length of the rails.) As the carriage moves past the release point the guide bars are pinched between the guide rails by the tension ($T \approx 1000$ N) of the upper rail preload springs, f, and the carriage is decelerated at a constant rate of $uT/M \approx 1000 \text{ ms}^{-2}$ (or about 100 G's) where u is the coefficient of sliding friction (.42 for steel on steel) and M is the carriage mass (.382 kg).

Figure 5. Schematic of Atlas Hail Gun

4.D. Simulated Hail Impact Test Data

Two sets of summary data are presented in Table III, one from impact testing conducted at Altas, one from testing conducted by Mr. Milton Smith at Texas Tech University [5]. These data sets are presented for comparison with the "maximum probable hailstone size" predicted in Ref. [1] and summarized in Table I of the present report.

For all three glazing types summarized in Table III, test specimens were new (not aged). Impact resistance of some glazing materials may change with age.

The definition of damage is different for each glazing type in Table III. For thin films, puncture by an ice sphere can clearly be considered damage. Residual indentation after impact may be considered damage if the glazing later sags to the absorber. For the thin films, the range of conditions after impact is noted under "Comments", the hailstone size range is noted in the left-hand column.

Cracking of the Fiberglass reinforced plastic (FRP) glazing can clearly be considered damage. Crazeing, a white scar on the FRP consisting of an intricate series of micro-cracks, may or may not be classified as damage. Tests would be required to determine if the function of the glazing were impaired. However, no judgment is made here as to whether crazeing results in decreased performance of the glazing or in increased susceptibility to future impact damage.

Damage to the tempered glass panels is well defined. Either breakage results or it does not. However, the stone size (or impact energy) resulting in breakage is not consistent from test specimen to test specimen; there is, rather, a wide distribution of damage thresholds for a given sample of glass panels. For comparison with the "maximum probable hailstone size" in Table I, the mean of this distribution is the most convenient index of damage. This is the hailstone size (or impact energy) at which 50 percent of the glass panels break, and 50 percent remain intact.

There is some variation in mass between molded ice spheres and between individual impact velocities of the same size hailstone. For this reason, the mean hailstone size, $\bar{D}$, and the mean kinetic energy, $\bar{E}_K$, are included in Altas' data in Table III.

Table III — Impact Test Data

THIN FILMS (data from [5])

<u>Hailstone size</u>	<u>Comments</u>
2.5 cm	No damage - residual indentations
3.18 cm - 3.8 cm	Residual indentations - glazing punctured
3.8 cm - 4.5 cm	Glazing punctured

NOTES: Reports of thin films punctured by smaller hailstones with protuberances. Thin films particularly sensitive to puncture near edges of collector panel [5].

FIBERGLASS REINFORCED PLASTIC, .040 thick (Atlas test data)

<u>D</u>	<u>E_K</u>	<u>Comments</u>
4.7 cm	15.7 Joules	Slight crazing (see text)
5.4 cm	32.5 Joules	Cracking

TEMPERED GLASS

1/8" thickness (data from [5])

<u>Hailstone Size</u>	<u>Comments</u>
3.8 cm	No damage
4.5 cm - 5.1 cm	50 percent breakage threshold in this range

5/32" thickness (data from [5])

5.1 cm	No damage

NOTE: Larger ice spheres were not impacted against 5/32" glass.

3/16" thickness (Atlas data)

<u>D</u>	<u>E_K</u>	<u>Comments</u>
5.4 cm	32.2 Joules	0% breakage rate
6.7 cm	87.4 Joules	24% breakage rate

In addition, the resistance of wire mesh screen to impact by large hail was tested. Screen was mounted in a 4 ft. x 4 ft. frame 12 inches in front of a panel of single strength untempered glass. Impact of a 6.7 cm hailstone at terminal velocity was absorbed by the screen and the glass remained intact. However, the impact resulted in plastic deformation of the screen.

Judging from simulated hail impact testing, the thin films begin to be left with residual indentations after impact by 2.5 cm stones. The thin films are punctured by impact of 3.8 cm stones or larger. However, there are reports of smaller hailstones with protuberances causing puncture [5].

The fiberglass reinforced plastics (.040 thick) will withstand impact by a 4.7 cm stone with slight crazing. Cracking results with impact by stones 5.4 cm or larger.

The 50 percent breakage threshold for 1/8 inch tempered glass is reached at a hailstone smaller than 5.1 cm; 5/32 inch tempered glass will withstand a 5.1 cm hailstone with no damage; 3/16 inch tempered glass will withstand impact by a 6.7 cm stone with minimal damage. The 50 percent breakage threshold for 5/32 inch and 3/16 inch tempered glass has not been determined.

It is interesting to compare these results with conclusions made in Ref. [7], which states "The breakage rate for 1/8 inch tempered glass can be expected to be no greater than 5 percent for hailstones of 3 to 4 inches in diameter." As discussed in Section 4.A., there is no evidence that, although 3 to 4 inch hailstones were observed in the Fort Collins storm, these stones actually struck any solar collectors in the storm's path. The threat of hail damage to solar collectors glazed with 1/8 inch tempered glass does appear negligible, not because 1/8 inch tempered glass can withstand impact by 3 to 4 inch hailstones, but rather because such stones are extremely rare — even when a storm containing such stones is encountered.

5. HAIL PROTECTION STRATEGIES

5.A. Screens

In Australia, in an area known to encounter "exceptionally severe" [9] hailstorms, 1/2 inch galvanized wire was suspended above a solar installation. The collector efficiency was reportedly reduced by about 12 percent [9]. The effectiveness of the screen as a protection device was not reported.

There are two costs associated with use of a screen as a hail protection device: 1) the initial cost of the screen, support stand, and installation; 2) the collector efficiency lost as a result of shading. In Section 5.B., the shading effect of a screen is evaluated, and calculations are made for two cases, one hypothetical and one for the screen used in Australia. It is shown that the second cost noted above is sufficiently high to all but prohibit the use of screens as protection devices. Based on these results, the first (and by comparison, insignificant) cost is not evaluated. In some areas an additional cost is the annual removal and reinstallation of the protection device. In the midwest and on the Great Plains, hailstorms occur almost exclusively during the summer. In areas where snow falls, a protection device might serve to retain snow longer than the collector itself, reducing efficiency. Thus, the protection device might be more effectively removed every winter.

Mr. Milton Smith at Texas Tech. University has effectively used nylon mesh as an active (i.e., deployed when a storm threatens and removed afterwards) protection device for parabolic reflectors in a demonstration project [5]. The mesh has survived laboratory impact tests of 5 cm hailstones without damage. Thermal performance loss calculations or measurements have not been made, since the mesh is not intended as a passive device. The strength of the nylon mesh, however, suggests that there are possibly synthetic materials whose transparency or translucency permit their use as cover screens without resulting in an unacceptable reduction in collector efficiency.

It is interesting to note that the collector installation protected by screens in Australia was glazed with single strength untempered glass [9]. Quite possibly more impact resistant glazing materials were not readily available at that time (May 1956).

5.B. Shading Effect of a Screen

The blockage of direct and diffuse solar energy produced by a screen can have a significant effect on the energy collection, so that it is important to get an analytical evaluation of this effect.

Several types of screens can be considered:

- a. Square-mesh screens, in which the wires cross each other at right angles and are welded at the intersections.
- b. Hexagonal meshes, in which the wires run generally parallel and are twisted together at intervals.

These mesh arrangements are shown in Figure 6 below. It is felt that screens of the "chain-link" type, in which the wires are linked loosely together, will not be stiff enough to be useful.

The sun strikes the screen at different angles during the day. The basic relationship needed to describe the shading produced by the screen with different angles of solar incidence is the shading produced by a round wire with an arbitrary angle of solar incidence, as shown in Figure 7 below. It is assumed the solar energy reflected by the wires into the collector is negligible.

Using Figure 7, it is clear that the two "incidence angles" ϕ' and ϕ are simply related by the relation:

$$\tan \phi' = \cos \theta \tan \phi \quad (5.1)$$

Examining the amount of shade produced by the wire, we can write:

$$\text{shade} = \frac{2R}{\cos \phi'} = \frac{D}{\cos \phi'} = \frac{D}{\cos[\tan^{-1}(\cos \theta \tan \phi)]} \quad (5.2)$$

$$\text{or } \frac{\text{shade}}{D} = \frac{1}{\cos[\tan^{-1}(\cos \theta \tan \phi)]} \quad (5.3)$$

A short table of values of equation (5.3) is shown in Table IV.

From values such as shown in Table IV, one can estimate the effect of

SQUARE MESH
SCREEN

HEXAGONAL MESH
SCREEN

Figure 6. Two screen mesh arrangements.

Figure 7. Shading geometry of a single wire.

Table IV. Shading Factor Shown in Equation (5/3) as a Function of ϕ and θ .*

$\phi \backslash \theta$	0	30	60	87.5	90
0	1.000	1.1547	2.000	22.9256	∞
30	1.000	1.1180	1.8028	19.8604	∞
60	1.000	1.0408	1.3229	11.4955	∞
90	1.000	1.000	1.000	1.000	1.000

*Note that in the other quadrants of θ the function is symmetrical.

orientation of the mesh on net shading (or on transmissivity). Even at a value of $\theta = 70^\circ$ (at which normally collection is very low) it is easy to show that orientation of a square mesh varies shading by only about 10 percent (and hence transmissivity even less). A hexagonal mesh is even less sensitive to orientation. In the hexagonal mesh the only worthwhile orientation involves aligning the double (twisted) wires parallel to an E-W, and not a N-S axis. If this is done, then the double wires will never cast a very wide shadow.

It seems accurate enough, and extremely desirable, to neglect the slight changes in transmissivity with the value of θ , since mesh orientation makes little difference anyway. We need two transmissivities:

- The average hemispherical transmissivity, based on diffuse (Lambert) radiation coming in and averaged over the hemisphere.
- The directional transmissivity, based on radiation coming in at some angle ϕ , averaged for $0 < \theta < 360^\circ$.

We can perform the necessary integrations by working with sections of the wire and the clear area associated with it. These wire-area combinations are shown below in Figure 8.

The transmissivity associated with the shading effect of one of these wires illuminated with angles θ and ϕ can be written using equation (5.3).

$$\begin{aligned} \tau(\phi, \theta) &= 1 - \frac{L \times \text{shade}}{A} \\ &= 1 - \frac{LD}{A \times \cos[\tan^{-1}(\cos\theta \tan\phi)]} \end{aligned} \quad (5.4)$$

In Equation (5.4) the values of the area A are as given in Figure 8 for square and hexagonal meshes. This function must be used to find an average transmissivity at particular values of ϕ , in order to work with direct solar energy, and a hemispherical average must be used to handle the diffuse energy.

To determine the transmissivity at a particular value of ϕ , we can write, using Equation (5.4):

$$\begin{aligned} \tau_\phi &= \frac{1}{2\pi} \int_0^{2\pi} \tau(\phi, \theta) d\theta \\ &= 1 - \frac{LD}{2\pi A} \int_{\theta=0}^{\theta=2\pi} \frac{d\theta}{\cos[\tan^{-1}(\cos\theta \tan\phi)]} \end{aligned} \quad (5.5)$$

Figure 8. Shading of square and hexagonal screens.

Where the 2π factor comes from the normalizing requirements imposed by:

$$\int_{\theta=0}^{\theta=2\pi} d\theta = 2\pi, \quad (5.6)$$

and again the area A comes from Figure 8.

Similarly, to average over the hemisphere we can use Lambert relations for the diffuse (isotropic) radiation to obtain:

$$\begin{aligned} \tau_H &= \frac{1}{\pi} \int_{\phi=0}^{\phi=\pi/2} \int_{\theta=0}^{\theta=2\pi} \tau(\phi, \theta) \sin\phi \cos\phi \, d\phi \, d\theta \\ &= 1 - \frac{LD}{\pi A} \int_{\phi=0}^{\phi=\pi/2} \int_{\theta=0}^{\theta=2\pi} \frac{\sin\phi \cos\phi \, d\phi \, d\theta}{\cos[\tan^{-1}(\cos\theta \tan\phi)]} \end{aligned} \quad (5.7)$$

Where the π factor comes from the normalizing requirements imposed by:

$$\int_{\phi=0}^{\phi=\pi/2} \int_{\theta=0}^{\theta=2\pi} \sin\phi \cos\phi \, d\phi \, d\theta = \pi \quad (5.8)$$

Some comments on these equations follow:

- For square meshes Equation (5.5) and (5.7) can be used essentially as is, since all wires are equal.
- For hexagonal meshes every third wire is double, so it is desirable to use as effective wire diameter $\frac{4}{3}D$.
- Using as wire length the full wire length leads to some inescapable mutual shading at the corners which is pretty negligible and is conservative besides.
- At very glancing angles the shade area might get larger than the standard cell area so that effective transmissivity might become negative. The calculation scheme must be set up so as to make sure $\tau(\phi)$ never becomes less than zero.

- e. It should be noted that the wire length, diameter and mesh area are outside of the integrals. This seems to suggest that the best way to perform calculations is to evaluate first the integral shown in Equation (5.5) for a list of values of ϕ . Then specific values of L, D and A are used to prepare an associated $\tau(\phi)$ list in which no entry is allowed to become negative (see d. above). To get hemispherical values we then use the relation:

$$\tau_H = 2 \int_{\phi=0}^{\phi=\pi/2} \tau(\phi) \sin\phi \cos\phi d\phi, \quad (5.9)$$

Where again the factor of 2 is a normalization requirement imposed by the fact that:

$$\int_{\phi=0}^{\phi=\pi/2} \sin\phi \cos\phi d\phi = \frac{1}{2} \quad (5.10)$$

A short FORTRAN program was written to calculate values of τ_ϕ and τ_H following these equations, for both square and hexagonal meshes. This program was exercised for various mesh types, and is shown in Appendix B for a mesh with a side of 17.857 times the wire diameter equivalent to a 1/2 inch mesh with wires of 22 S.W.G. (.028 inch). This is the mesh which has been used in Australia [9]. Included in Appendix B are results from this program, and also results for a mesh with side 25 times the wire diameter. It is clear the transmissivity is quite high up to very glancing angles at which collection is negligible anyway. The estimate of 10 - 15 percent loss made in the Australian literature seems quite plausible. In view of the limited promise offered by screens, it seems unnecessary to perform a rigorous economic analysis of screens as hail protection devices.

6. VANDALISM

As part of the present contract, Altas has investigated the threat of vandalism to solar collectors. A thorough characterization of the incidence of vandalism would involve following a large sample of commercially sold collectors to their destinations. These collectors would then be monitored periodically to determine the incidence of vandalism. The feasibility of such an undertaking is questionable.

For most flat plate collectors sold in the United States (i.e. not onsite built collectors) replacement cover plates are most conveniently purchased through the distributor. In turn, distributors most conveniently purchase replacement covers through the manufacturer. Therefore, if manufacturers are interested in the incidence and cause of glazing breakage, the information is available to them. In an effort to quantify the incidence of vandalism to solar flat plate collectors, Altas contacted six major manufacturers of flat plate collectors in the United States. All of these felt that cases of vandalism and other breakage would be known by them. At least two personnel in each company were asked the following questions:

- 1) Is it feasible for a customer to replace the glazing on your collector without specially ordering through your company?
- 2) How many collector square feet did your company sell: a) in 1977? b) in 1978? c) so far in 1979 (mid-June)?
- 3) How many instances of glazing breakage have been reported to your company since January, 1977: a) Vandalism? b) Hail? c) Other?

Telephone conversations were then followed up with written inquiries to validate responses. Any information obtained with a "yes" answer to question #1 was not used for evaluation.

To determine the incidence of vandalism, one is concerned not only with the number of installed collectors (or collector square feet installed) but of the duration they have been exposed to possible vandalism — their "exposure index".

At the time of this work (June 1979) units sold in 1977 had been installed for between 1-1/2 and 2-1/2 years, or roughly, an average of

2 years. Units sold in 1978 had been installed an average of 1 year, units sold in 1979 an average of .25 years. Therefore if x_1 collector square feet were sold by a company in 1977, x_2 collector square feet in 1978, and x_3 collector square feet so far in 1979, the "exposure index" — the number of "square feet years" of exposure — could be considered to be:

$$(2 x_1) (1 x_2) (.25 x_3) \text{ ft}^2 \text{ years}$$

This approach has been taken in the present report to calculate roughly the incidence of vandalism to flat plate collectors in the United States. That this is not rigorously quantitative is recognized.

To summarize the data obtained, for slightly less than one million "collector square feet years" in the United States since 1977, 10 cases of known vandalism were reported, 2 cases of hail breakage, and 34 cases of other breakage. The locations of breakage are not known, nor are the glazing types. The collector square feet broken by vandals, hail or other phenomena was not available. It should be noted that the accuracy of data obtained through manufacturing personnel is unknown. However, if we assume a severe case, that each incident of vandalism resulted in 1,000 ft^2 of glazing breakage, we can hopefully offset serious biases in this methodology. Thus, we have a vandalism rate of probably no greater than 1 percent of the installed collector square feet in any given year.

All personnel contacted by Atlas felt that vandalism was a very minor problem to solar collectors. Some noted limited areas where vandalism had been a problem, not only to solar collectors, but to windows, cars, etc. Areas noted by manufacturing personnel for vandalism were high traffic areas near freeways, near schools, and in industrial settings. Noted also were precautions that have been successfully taken to limit vandalism: mounting collectors on rooftops, behind buildings, enclosing collectors by fences.

Clearly, the threat of vandalism to flat plate collectors must be evaluated on a case-by-case basis. In some areas, precautionary measures will be necessary. In most, these measures will not be required. In any case, vandalism is a very low incidence phenomenon.

7. CONCLUSIONS

By comparing the preliminary data on the incidence of damaging hail (Table I) with the impact test data of Table III, one can roughly assess the practical hail resistance of various glazings. In performing such an assessment, three points must be reiterated:

- 1) The results documented in Ref. [1] and summarized in Table I must be considered preliminary until hailstone size distribution data are fully analyzed, and until the incidence of damaging hail is evaluated in more locations.
- 2) The biases in simulated hail impact testing (from which the data in Table III have come) are quite conservative and should be further investigated.
- 3) Impact resistance of the plastic glazing materials appears to decrease with aging.

Without hail protection devices, the thin films do not appear to be a viable glazing material for use in the "hail belt". Hailstone sizes that will occur everywhere in the "hail belt" (even within a 5 year period) will result in residual indentations at the very least. Even the hailstone size range that results in puncture is likely to be encountered in some locations for various values of A and K.

As discussed in Section 1, the choice of a glazing material for a particular application depends not only on its resistance to damage by hail, but on a wide range of characteristics. If thin films are used in the "hail belt", an external hail protection strategy appears to be necessary. If cover screens are used in this case, the benefits of the thin films will have to exceed the cost of lost collector efficiency noted in Section 5.B. or, other protection devices will have to be devised.

Based on Tables I and III, the fiberglass reinforced plastics will be subject to crazing in severe hail areas. Whether crazing does or does not constitute damage is not evaluated here. The hailstone size that causes cracking is at the upper end of the maximum probable hailstone size range of Table I, i.e., cracking may result in severe hail areas. 1/8 inch tempered glass appears to be susceptible to damage in severe hail areas in the "hail belt", such as Cheyenne, Wyoming. The

susceptibility of 5/32 inch tempered glass cannot be determined from the data in Table III.

It is quite clear that 3/16 inch tempered glass will demonstrate a negligible breakage rate even in the most severe areas of the hail belt. The use of 3/16 inch tempered glass in severe hail areas for applications where even negligible breakage is unacceptable constitutes a very viable hail protection strategy.

The incidence of vandalism to solar collectors appears negligible at present.

Efforts by the Department of Energy to develop standards and codes for solar equipment to withstand hail should be carefully considered in light of the data available at present.

8. RECOMMENDATIONS

The work documented in Ref. [1], the assessment of the incidence of large hailstones, should be extended. Due to the extensive calculations involved, the incidence of damaging hail (which is a geographically variable phenomenon) has been evaluated in only four locations in the "hail belt". Results for other locations might be judiciously extrapolated from these data, but this approach would be ill-advised for the purposes of optimizing collector design or for the development of standards or codes for solar equipment to withstand hail.

Extensive hailday data remain to be evaluated as well as hailstone size distribution and hailfall density distribution data. Further work in this area would extend the predictions of the risk model developed in Ref. [1] to more locations and would also make these predictions more justifiable.

The biases of the current simulated hailstone impact testing have been noted in Section 4.A. Before the data gathered from these tests are applied to optimize collector design or develop "hail resistance" standards, these biases should be investigated.

A hail protection strategy not pursued in the present contract is that of designing collectors for easy replacement of damaged glazings. This possibility bears further investigation.

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Appendix A

Comments submitted to the Council of American Building Officials and the U.S. Department of Energy concerning Section B.108.2c of "The Proposed Model Document for Code Officials on Solar Heating and Cooling of Buildings" (see Ref. [14]).

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December 18, 1979

MC Ref. #066-79

B.S. Trant, Executive Director
Council of American Building Officials
2233 Wisconsin Avenue N.W.
Suite 560
Washington, DC 20007

Re: Section B.108.2c of the Second Draft of the "Proposed Model Document for Code Officials on Solar Heating and Cooling of Buildings."

Dear Mr. Trant:

At the most recent public meeting (December 7th in San Diego), held to discuss the proposed model document, Mr. Nick Chapman of FAFCO, Inc., presented objections to the present Section B.108.2c, which would require solar collectors to withstand impact by specified hail conditions. This letter is submitted as a supplement to his comments.

In a recent article in the ASHRAE Journal [1], David Pellish of the DOE stressed that:

- the purpose of the Model Document is to accelerate, "not impede the use of solar systems, construction techniques, and materials in building."
- the DOE has no interest "in endorsing any particular products to the exclusion of others in the market."
- the development of the Model Document is to enhance consumer confidence in solar technology.

Below, we present evidence that the section of the Model Document concerning hail damage risk and hail resistance or protection will not lead to these goals. In fact, we believe the present Section B.108.2c will very likely have the opposite effect in areas of the "hail belt" - impeding solar development, effectively endorsing certain products to the exclusion of others, and leading consumers to question the cost-effectiveness of mandatory protection against hailstone diameters they themselves have not seen in 20 or 30 years of residence.

Altas Corporation has for the past year worked under DOE funding to develop "Cost Effective Hail Protection Devices for Solar Flat Plate Collectors." As part of this contract, we have closely examined the risk of encountering damaging hailstones in various locales in the "hail belt" and have also studied the damage thresholds of flat plate collector glazings. In addition, we are in contact with numerous others in the field and have compiled a sizeable body of data concerning hail and the impact resistance of solar equipment. Our first technical report [2] under this contract is the best assessment to date of the "probable maximum hailstone diameter" that solar collectors should be designed to withstand. Our "probable maximum hailstone diameter" is equivalent to "D" of Section B.108.2c, which is also the hailstone diameter that solar collectors must withstand:

$$D = 0.3d$$

where

d = the mean annual number of haildays at the particular locale.

It is unknown to us how the expression $D = 0.3d$ has been derived, and upon which hail data it has been based - but this expression is entirely inconsistent with our results.

We concur with the desire to develop "rules of thumb" to protect solar equipment against hail breakage, but we find the present code, Section B.108.2c, entirely unsatisfactory. We believe that, at the present time, sufficient work has not been done (at Altas or elsewhere) to warrant the development of a "hail code". However, should the implementation of such a code be deemed absolutely essential at present, we believe a better code can and must be substituted for Section B.108.2c.

The first problem with the proposed code is that the probable maximum hailstone size, D , is not simply a function of the mean annual number of haildays, d . For simplicity of use, some of the parameters of which D is a function can be fixed. It should be noted that D increases with the size of the collector area, A , exposed to possible hail breakage, and with the number of years, K , of exposure. As an extreme example, consider that a 3 inch hailstone is more likely to strike somewhere in Denver during a five-year period than a given 10m^2 collector in the same period.

For simplicity of calculation, A and K can be set when writing codes. We assume that Section B.108.2c has been written for a typical space heating flat plate collector, 50m^2 , to resist breakage during its projected 20-year lifetime. On this basis, we will compare our results with the probable maximum hailstone size, D , specified in Section B.108.2c. It can be noted that if the comparison is based on other assumptions of A and K , similar conclusions are reached.

In any location in the "hail belt", hailstorms do not occur " d " times each year, but rather hailstorms are encountered fewer times some years, and more often during other years. A compilation of the number of haildays each year defines the "hailday distribution". In Section B.108.2c of the Model Document, the mean, d , of this distribution is used to calculate the probable maximum hailstone diameter, D . The code then specifies that solar collectors must withstand impact by a D inch hailstone.

Work at Altas has demonstrated, however, that the variance of the hailday distribution about the mean, is far more significant in determining the probable maximum hailstone diameter, D , than is the mean alone. Two hailday distributions (recorded in two

locations) can have the same mean yet radically different variances. Using the expression presently in the Model Document, retail stores would, in both locations, be forced to carry collectors that could withstand a D inch hailstone. In one location, these collectors may be significantly under-designed, and may experience unforeseen breakage; and in the second location may be significantly over-designed, proving to be far more expensive (and hence less cost-effective) than need be.

We concur with the need for building codes for solar collectors to withstand hail damage. However, codes based on insufficient or wrong information may be worse than no codes at all. At present, a characterization of the mean annual number of haildays and the variance of the hailday distribution in relation to the probable maximum hailstone size, D, has not been completed. Hopefully, Altas will continue the work that has begun in this area. Until such results are available, we recommend that Section B.108.2c be deleted from the proposed Model Document.

If, however, it is deemed essential that a code addressing resistance to hail damage be included in the Model Document at this time, Section B.108.2c is unsatisfactory. Even if it is desirable to ignore the effect of the hailday distribution variance, and to calculate hailstone damage risk only on the basis of the mean annual number of haildays, the expression $D = 0.3d$ is inaccurate. For example, if an average of nine haildays occur each year in a given location (as in Cheyenne, Wyoming) this expression would require collectors to withstand a $2\frac{3}{4}$ inch hailstone. To our knowledge, no flat plate collector glazing on the market will withstand perpendicular impact of such a hailstone (or, more accurately, perpendicular impact of a laboratory hailstone - a solid ice sphere).

Work at Altas has so far demonstrated that the probable maximum hailstone size that can be expected to strike a $50m^2$ collector in its 20-year lifetime in Cheyenne, Wyoming, is $\sim 1\frac{3}{4}$ inch. If protection devices (such as cover screens) were used to protect

against Section B.108.2c's 2-3/4 inch hailstone, there would be the added cost of the screen, mounting device, and installation, in addition to the resultant loss of collector thermal efficiency of perhaps 10 percent.

Suppose that use of the expression $D = 0.3d$ required protection against (or resistance to) a 2 inch hailstone, when in reality only a 1-1/2 inch hailstone would be encountered. A material that could withstand impact by a 1-1/2 inch hailstone but not a 2 inch hailstone (some of the thin films used on flat plate collectors, for example) would effectively be penalized in the marketplace. This is in fact not a hypothetical example. In the graph on the following page, we have plotted the probable maximum hailstone diameter as a function of the mean annual number of haildays. The four points represent four locations where hail damage risk has been evaluated (from Ref. [2]). A straight line has been fit to these points. The straight line proposed in Section B.108.2c has also been plotted for comparison. Clearly, there is significant discrepancy. Note that the example just cited will be found in areas with a mean annual number of haildays of ~ 6 .

In areas where hail damage is even likely to be a problem ($\sim 2-9$ mean annual haildays), we recommend protection against (or resistance to) hailstones of size:

$$D = 1.26 + .04d$$

This is based on the probable maximum hailstone size on a $50m^2$ collector exposed for 20 years. The most conservative requirement we could support is:

$$D = 1.70 + .04d$$

based on different assumptions regarding the hailstone size distribution (see Ref. [2]).

Note in the graph that D has been extrapolated from $d = 2$ down to $d = 0$. This extrapolation is probably severe. However, for regions where $d < 2$ per year, protection from projectiles predicted upon one of the above relations should probably be required anyway to control collector damage from other objects (golf balls, baseballs, vandalism, falling branches, wind blown objects).

In summary, we believe the present Section B.108.2c to be unsatisfactory, that it can create more harm than benefits; that there is at present insufficient information to justify writing a code for solar collectors to withstand hail damage; that the writing of such a code should be postponed until sufficient information is available. If it is deemed essential that such a code be included in the present Model Document in spite of the information we have presented, we have offered an alternative to Section B.108.2c.

Sincerely,
ALTAS CORPORATION

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Research Associate

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MC:cal

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encl: Ref. [2]

References

1. David M. Pellish, "DOE UPDATE: Solar Standards, Codes, Testing and Certificaton Program," ASHRAE Journal, November 1979, p. 53.
2. Cox, Michael and P.R. Armstrong, "A Statistical Model for Assessing the Risk of Hail Damage to any Ground Installation," Technical Report prepared for U.S. DOE under contract EM-78-C-04-4921, Report No. ALO/4291-1 (September, 1979).

Appendix B

Source code to calculate reduction in τ as a function of ϕ for square and hexagonal screen mesh. Results for two cases of screens (one of length to thickness ratio of 17.86/1; one of ratio 25/1) are included.


```

    DIMENSION PHISCR(90),TAUHEX(90),TAUSQU(90),WBLOCK(90),
1NDEGSH(90)
    WIRED=1.0
    WIREL=17.857
C    THE FOLLOWING DO LOOPS DO THE INTEGRATION PROCESS IN
C    EQUATION 5 OF THE REPORT SECTION ENTITLED SHADING EFFECT
C    OF A SCREEN,
    DO 2 J=1,90
    XPHISC=J
    PHISCR(J)=3.141593/180.0*(XPHISC-1.0)
    WBLOCK(J)=0.0

C    NOTE THAT DO LOOP 1 ONLY DOES 90 DEGREES, NOT 360.
C    ONLY 90 DEGREES ARE NEEDED, SINCE OTHER QUADRANTS ARE
C    SYMMETRICAL,
    DO 1 I=1,90
    YTHESC=I
    THESCR=3.141593/180.0*(YTHESC-0.5)
    DENOMS=COS(ATAN(COS(THESCR)*SIN(PHISCR(J))/COS(PHISCR(J))))
    DELTHE=3.141593/180.0
C    WBLOCK(J) IS THE BLOCKING COEFFICIENT INDEPENDENT OF
C    SPECIFIC SCREEN CONFIGURATION, WIRE DIAMETER, AND MESH
C    SIZE,
    WBLOCK(J)=WBLOCK(J)+DELTHE/DENOMS*2.0/3.141593
    1 CONTINUE
    2 CONTINUE
    CSQUAR=2.0*WIRED/WIREL
    CHEXAG=2.0*WIRED*4.0/3.0/WIREL/3.0**0.5
C    SETTING INITIAL HEMISPHERICAL TRANSMISSIVITY EQUAL TO ZERO.
    TAHXHM=0.0
    TASQHM=0.0
    DO 3 J=1,90
    FACHEM=SIN(PHISCR(J))*COS(PHISCR(J))*2.0*3.141593/180.0
    TAUHEX(J)=1.0-CHEXAG*WBLOCK(J)
    IF (TAUHEX(J)) 5,5,6
    5 TAUHEX(J)=0.0
    6 CONTINUE
    TAHXHM=TAHXHM+TAUHEX(J)*FACHEM
    TAUSQU(J)=1.0-CSQUAR*WBLOCK(J)
    IF (TAUSQU(J)) 7,7,8
    7 TAUSQU(J)=0.0
    8 CONTINUE
    TASQHM=TASQHM+TAUSQU(J)*FACHEM
    3 CONTINUE
    DO 9 J=1,90
    NDEGSH(J)=J-1
    WRITE (6,101) NDEGSH(J), WBLOCK(J), TAUSQU(J), TAUHEX(J)
101 FORMAT (5X,1F5.1,3F12.5)
    9 CONTINUE
    WRITE (6,102)
102 FORMAT (///)
    WRITE (6,103) TASQHM,TAHXHM
103 FORMAT (5X,2F12.5)
    END

```

ϕ	$\tau(\phi)$ square	$\tau(\phi)$ hex
0.0	0.88800	0.91378
1.0	0.88799	0.91378
2.0	0.88796	0.91376
3.0	0.88792	0.91372
4.0	0.88786	0.91368
5.0	0.88779	0.91362
6.0	0.88769	0.91354
7.0	0.88758	0.91346
8.0	0.88745	0.91336
9.0	0.88730	0.91324
10.0	0.88713	0.91312
11.0	0.88695	0.91297
12.0	0.88674	0.91282
13.0	0.88652	0.91264
14.0	0.88628	0.91246
15.0	0.88602	0.91225
16.0	0.88573	0.91204
17.0	0.88543	0.91180
18.0	0.88510	0.91155
19.0	0.88475	0.91128
20.0	0.88438	0.91099
21.0	0.88398	0.91069
22.0	0.88356	0.91036
23.0	0.88311	0.91002
24.0	0.88264	0.90966
25.0	0.88214	0.90927
26.0	0.88161	0.90886
27.0	0.88105	0.90843
28.0	0.88046	0.90798
29.0	0.87984	0.90750
30.0	0.87918	0.90699
31.0	0.87849	0.90646
32.0	0.87776	0.90590
33.0	0.87699	0.90531
34.0	0.87618	0.90468
35.0	0.87533	0.90403
36.0	0.87443	0.90334
37.0	0.87348	0.90261
38.0	0.87249	0.90184
39.0	0.87144	0.90103
40.0	0.87033	0.90018
41.0	0.86916	0.89928
42.0	0.86793	0.89833
43.0	0.86663	0.89733
44.0	0.86526	0.89627
45.0	0.86381	0.89516
46.0	0.86227	0.89398
47.0	0.86065	0.89273
48.0	0.85893	0.89141
49.0	0.85711	0.89000
50.0	0.85518	0.88852
51.0	0.85313	0.88694
52.0	0.85095	0.88526
53.0	0.84864	0.88348
54.0	0.84617	0.88158
55.0	0.84353	0.87955

(con.)

Reduction in τ as a
function of ϕ for a
screen of length to
thickness ratio:
17.86/1.

56.0	0.84072	0.87738
57.0	0.83771	0.87507
58.0	0.83448	0.87259
59.0	0.83102	0.86992
60.0	0.82730	0.86705
61.0	0.82329	0.86397
62.0	0.81896	0.86043
63.0	0.81427	0.85702
64.0	0.80918	0.85311
65.0	0.80364	0.84885
66.0	0.79760	0.84420
67.0	0.79099	0.83911
68.0	0.78373	0.83351
69.0	0.77572	0.82735
70.0	0.76685	0.82052
71.0	0.75698	0.81292
72.0	0.74594	0.80443
73.0	0.73353	0.79487
74.0	0.71948	0.78406
75.0	0.70346	0.77172
76.0	0.68505	0.75755
77.0	0.66368	0.74110
78.0	0.63861	0.72180
79.0	0.60883	0.69888
80.0	0.57292	0.67123
81.0	0.52880	0.63727
82.0	0.47341	0.59463
83.0	0.40188	0.53956
84.0	0.30611	0.46584
85.0	0.17154	0.36225
86.0	0.00000	0.20634
87.0	0.00000	0.00000
88.0	0.00000	0.00000
89.0	0.00000	0.00000

0.22913

Hemispherical calculation for
square mesh

0.86754

Hemispherical calculation for
hexagonal mesh

ϕ	$\tau(\phi)$ square	$\tau(\phi)$ hex
0.0	0.92000	0.93842
1.0	0.91999	0.93841
2.0	0.91998	0.93840
3.0	0.91995	0.93837
4.0	0.91990	0.93834
5.0	0.91985	0.93830
6.0	0.91978	0.93825
7.0	0.91970	0.93818
8.0	0.91961	0.93811
9.0	0.91950	0.93803
10.0	0.91938	0.93794
11.0	0.91925	0.93784
12.0	0.91910	0.93773
13.0	0.91894	0.93760
14.0	0.91877	0.93747
15.0	0.91858	0.93733
16.0	0.91838	0.93717
17.0	0.91816	0.93700
18.0	0.91793	0.93682
19.0	0.91768	0.93663
20.0	0.91741	0.93642
21.0	0.91713	0.93621
22.0	0.91683	0.93597
23.0	0.91651	0.93573
24.0	0.91617	0.93547
25.0	0.91581	0.93519
26.0	0.91544	0.93490
27.0	0.91504	0.93459
28.0	0.91461	0.93427
29.0	0.91417	0.93393
30.0	0.91370	0.93357
31.0	0.91321	0.93319
32.0	0.91269	0.93279
33.0	0.91214	0.93236
34.0	0.91156	0.93192
35.0	0.91095	0.93145
36.0	0.91031	0.93095
37.0	0.90963	0.93043
38.0	0.90892	0.92989
39.0	0.90817	0.92931
40.0	0.90738	0.92870
41.0	0.90654	0.92806
42.0	0.90566	0.92738
43.0	0.90474	0.92667
44.0	0.90376	0.92591
45.0	0.90272	0.92511
46.0	0.90162	0.92427
47.0	0.90047	0.92338
48.0	0.89924	0.92243
49.0	0.89794	0.92143
50.0	0.89656	0.92037
51.0	0.89509	0.91924
52.0	0.89354	0.91805
53.0	0.89188	0.91677
54.0	0.89012	0.91541
55.0	0.88824	0.91397

Reduction in τ as a
function of ϕ for a
screen of length to
thickness ratio:
25/1.

(con.)

ϕ	$\tau(\phi)$ square	$\tau(\phi)$ hex
56.0	0.88623	0.91242
57.0	0.88408	0.91076
58.0	0.88177	0.90899
59.0	0.87930	0.90709
60.0	0.87664	0.90504
61.0	0.87378	0.90283
62.0	0.87068	0.90045
63.0	0.86733	0.89787
64.0	0.86370	0.89508
65.0	0.85975	0.89203
66.0	0.85543	0.88871
67.0	0.85071	0.88508
68.0	0.84552	0.88108
69.0	0.83980	0.87668
70.0	0.83346	0.87180
71.0	0.82642	0.86637
72.0	0.81853	0.86031
73.0	0.80967	0.85348
74.0	0.79963	0.84576
75.0	0.78819	0.83695
76.0	0.77504	0.82682
77.0	0.75977	0.81507
78.0	0.74187	0.80129
79.0	0.72060	0.78492
80.0	0.69494	0.76517
81.0	0.66343	0.74091
82.0	0.62387	0.71045
83.0	0.57277	0.67112
84.0	0.50437	0.61846
85.0	0.40825	0.54447
86.0	0.26358	0.43310
87.0	0.02175	0.24694
88.0	0.00000	0.00000
89.0	0.00000	0.00000

0.87686

Hemispherical calculation
for square mesh

0.90476

Hemispherical calculation
for hexagonal mesh