HAIL RISK MODEL FOR SOLAR COLLECTORS

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ABSTRACT

This report presents the results of a study assessing the probability of solar arrays being struck by hailstones of various sizes as a function of geographic location and service life. The study complements parallel studies of solar array sensitivity to hail damage, the final objective being an estimate of the most cost effective level for solar array hail protection. A key element of this study involves the generation of a statistical model describing the probability of impact by hailstones of various sizes and estimating the mean time between hits.

I. INTRODUCTION

A. Objective

A program is underway to develop reliable and economically competitive terrestrial photovoltaic solar arrays. These arrays consist of large areas of silicon solar cells encapsulated by a transparent glass or plastic cover. Such large areas of arrays are vulnerable to damage. Hailstones large enough to damage a solar collector of any type occur frequently enough to be of concern in some areas of the country.

The problem which arises is the quantification of risk due to hailstone damage. Unfortunately, very little data are available to model the risk. Values of certain parameters are required in order to perform studies such as determining the cost tradeoffs between providing added protection to solar arrays and assuming the risk of having to replace array modules prior to obsolescence.

Previous work on hail risk has primarily centered on crop damage due to hail. The threshold hailstone size for crop damage is significantly smaller than that which would cause damage to a structure such as a solar array. Therefore, the area of concern in the latter case encompasses the occurrence of events which are rare, but nevertheless, of sufficiently high probability to warrant investigation.

This study involves the development of a hail-risk model using data available only in limited amounts. The model and results reported here are equally applicable to any type of solar collector which is susceptible to impact damage.

B. Geographical Areas and Hail

Changnon (Refs. 1 and 2) has identified a number of high-frequency hail areas. However, one must be careful in citing an area as a high hail area. Because of the climatic differences between areas, one high hail area may be a threat to solar arrays, while another is not. The midwest and central portion of the U.S. to the Rockies are considered to be high hail areas. There are many recorded occurrences of hailstones large enough and with sufficient areal density to cause major damage to solar panels over areas of tens of square miles. On the other hand, there are high hail areas on the West Coast which usually produce only small hail. The hail is damaging to fruit crops, such as pears, because small blemishes produced by the hail make the fruit unfit for sale. This type of hail would pose no threat at all to a solar array.

The highest frequency hail areas are shown in Fig. 1, which gives the expected number of days with hail in 20 years according to Changnon (Ref. 2). One of the difficulties in attempting to identify areas of high hail occurrence is that the occurrence is normally recorded only where there are stations or observers of some type. For example, one form of hail information may be found in the records of crop losses due to hail. A low value in an uninhabited area may be due simply to lack of observations. On the other hand, solar arrays would most likely be deployed in inhabited areas, where information on the occurrence of hail is usually available. One exception is the sparsely populated southwest desert area, where one may assume that the occurrence of large hail is highly unlikely, even without substantiating records.

Although other areas of the country experience hail, some in large quantities, the major threat from larger hailstones (greater than 1 to 1.25 inches) lies in the central area shown in Fig. 1.

As indicated above, Fig. 1 gives the average expected number of hail days. A high hail frequency does not necessarily mean high incidence of large hail. This point will be further developed later.

II. DATA ASSESSMENT

The only hail data or information recorded in a systematic and continuous way is the point frequency of hailstorm occurrence. Other hail parameters have been measured at small numbers of locations for short periods of time and in many instances, with the use of volunteer observers. In addition, much of the data gathered are not in a reduced form which could be applied to this problem. Furthermore, hailstorms are a very limited phenomenon. A hail area is considered from the standpoint of two different types of areas. First, hailstorm activity involves an envelope of semi-continuous hail areas called a hailswath. The average dimension found for storms in Illinois are 6 miles by 25 miles, with an average of two swaths per hail day about 20 miles apart. The following information was obtained in Alberta, Canada: for hailswaths considered there, 34 percent were

Proceedings of the 1978 Institute of Environmental Sciences 24th Annual Technical Meeting
Fort Worth, Texas, April 18-20, 1978, pp. 278-286.

Fig. 1. Total number of days with hail in an average 20-year period

10 to 30 miles long, 31 percent were 31 to 50 miles long and 35 percent were more than 50 miles in length (Ref. 1). If one takes into account the hailswaths measured in Alberta, one would expect hailswaths to cover areas from 150 mi^2 to 1000 mi^2.

The second type of hail area is the hailstreak which is a single volume of hail produced in a storm. Many hailstreaks form a major hailswath indicating that certain large storms produce several separate volumes of hail. The median size of a hailstreak found in Illinois was 7.9 mi^2 miles or the average dimensions were 1.1 miles by 5.9 miles (Ref. 1).

Since a hailswath is a semi-continuous area of hail, the actual continuous area covered is better determined by considering the hailstreak.

A. Number of Hailstorms per Year

Values for the number of hailstorms per year in the central part of the U.S. are provided in Fig. 1 as a function of geographical location. The values provided in this figure and values for the rest of the U.S. obtained from Ref. 3 are used to arrive at the results presented later.

The number of hailstorms per year is usually given as average annual number of hail days. This is the number of days that hail was reported by a given observation station or observer. Thus each hail day is assumed to be one occurrence of hail. The number of hail days is used here as a point value.

B. Number of Expected Hailstones of a Given Diameter

The information available on hailstone size distribution is sparse. Several studies have been performed which obtained information on hailstone size, but only represented a limited area of the country. In addition, numerous activities have involved gathering hailstone data (Refs. 1, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, and 17). Most of the data are based on reports of volunteer observers. The accuracy of such data may be open to question. However, that is not the major problem in attempting to derive a hailstone size distribution as a function of geographical location. The main problem is the lack of data for most areas. The data taken to date have been confined mainly to three general areas, Illinois, Colorado (near Denver), and Alberta, with some data taken in the Dakotas, Arizona, Oklahoma, and New England.

Therefore, to develop even a cursory geographic distribution for hailstone size, broad generalizations will have to be made. Based on a discussion with Changnon and use of Ref. 3, the Continental U.S. has been divided into three areas (see Fig. 2). The available data from each region were plotted and the envelopes drawn which encompassed all of the available

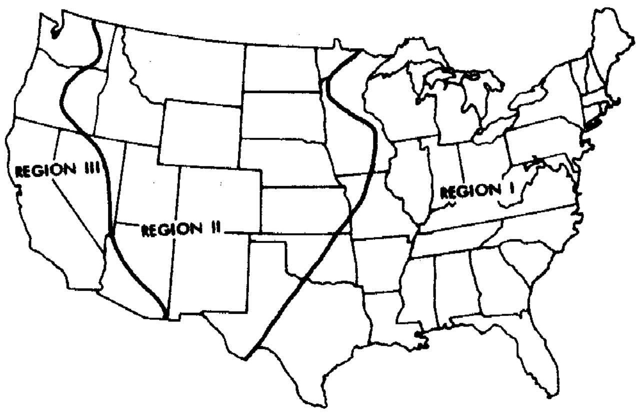

Fig. 2. Hail regions

data (see Figs. 3 and 4). No envelope was constructed for Region III because only one data set is available. The graphs are cumulative probability plots, giving the probability of obtaining hailstones of a given diameter or greater, given that a hailstorm has occurred.

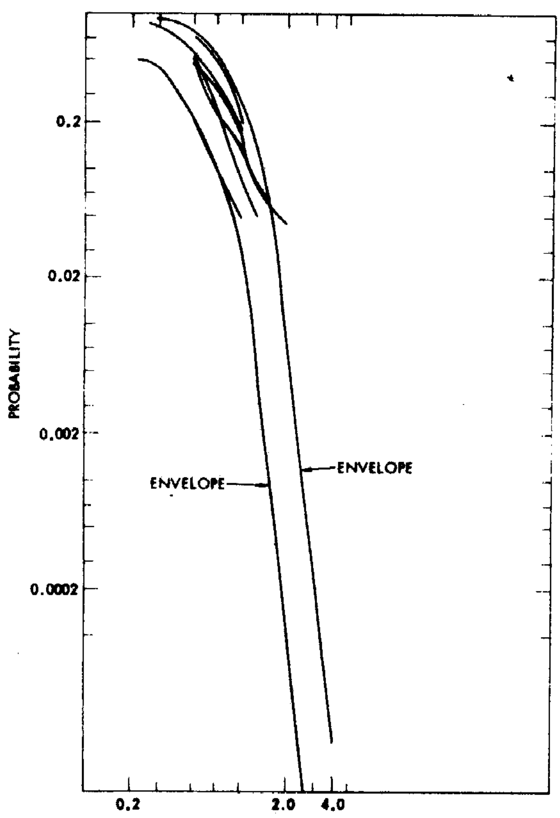

Fig. 3. Probability of obtaining hailstones of diameter equal to or greater than D (data from Illinois)

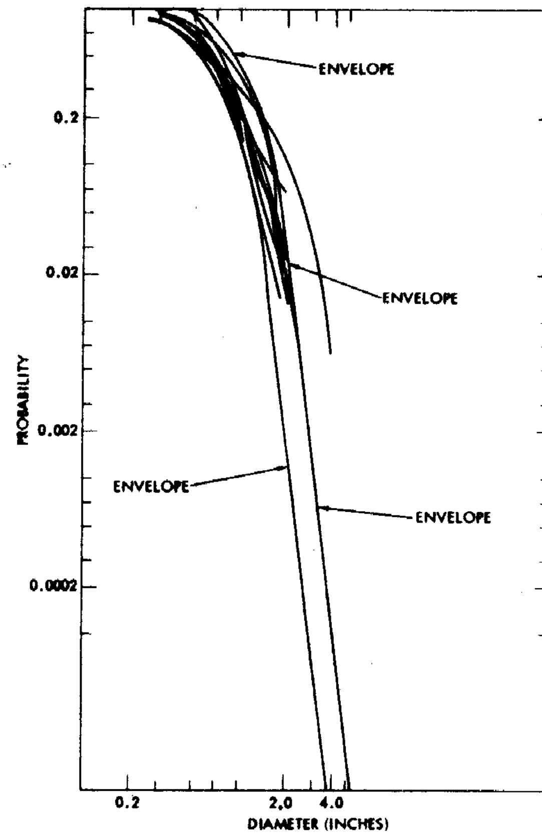

Fig. 4. Probability of obtaining hailstones of diameter equal to or greater than D (data from Colorado, Alberta, and Oklahoma)

Most of the data available are for hailstone diameters of 1 inch or less. In order to obtain probabilities for larger diameters, an extrapolation has to be made. The plots in Figs. 3 and 4 are log-log plots. Two envelope curves were plotted so that the slope matched that of the plotted area. An upper limit and a lower limit envelope were plotted in order to bound the hailstone size data. These envelopes provide a range of values which encompass the available data. In effect, they provide an upper and lower limit bound to the expected size distribution. The slopes of the plotted data are continuously varying. Thus, it can be seen from the figures that a simple extension of the curve for diameters of 1 inch or less, at the last slope recorded would give a curve outside of the upper envelope curve. Therefore, the envelope curves are drawn with a slope much steeper than the slope of the curves which represent smaller sizes. The basis for doing this is simply engineering judgment derived from discussions with personnel working with hail data. It was felt to be unreasonable to plot cumulative probability curves which have a constant slope from smaller sizes to the larger sizes.

One may question why the cumulative probability curves are extended to larger sizes, if so little data are available for these larger sizes. As cited in the introduction, there have been sufficient reports of large size hailstones so that their existence is a certainty. Therefore, except in Region III, in Fig. 2, they cannot be ruled out. Therefore, the probability distribution provided for large stones is the "best guess" at this point. A range is provided by the envelopes. An average value would be located in the central region of the area bounded by the envelopes.

Table 1 gives the results for the three regions shown on Fig. 2 which are taken from the plots in Figs. 3 and 4, and from Ref. 11 (for Region III). The values given in Table 1 are the probability of getting hailstone of a given diameter or larger. The values for Regions I and II were obtained from the envelopes of the plots shown in the figures. The plots shown were constructed from data taken from the references indicated. The data provided in the references were for different size intervals and are a conglomeration of data obtained from hailpads and data obtained from observers. Changnon (Ref. 7) found that for hailstones larger than 0.5 inch the size distribution derived from observers agreed well with those derived from hailpad data. In order to account for uncertainties in data acquisition, especially when taken from observer reports, a data interval about a given size was used. For example, in obtaining the plots, the value used for the probability for diameters greater than 1 inch may have included reports for diameters from 0.8 inch to 1.25 inches. In some cases, data were reported for diameters greater than 1.0 inch, greater than 0.75 inch, etc., and due to the nature of data, the information was used exactly as reported. In other words, a judgment was made on what data to include in given size intervals. The closeness of the curves suggests that this was a reasonable approach to take.

The cumulative probability distribution for Region III has no sizes greater than 1 inch. There are very few reports of sizes greater than 1 inch in this area. The data used for this region were taken from Ref. 11 and represent the hail environment on top of a mountain peak 9184 ft (2800 m) above sea level. Therefore, this environment represents an upper limit for Region III and is probably too severe for lower elevations. An important question is whether hail of a significant size occurs in the flat areas of the southwest with an abundance of sunshine. Discussions with personnel at the University of Arizona at Tucson, the National Weather Service at Tucson, and the Atmospheric Science Lab at White Sands Missile Range (Ref. 18) indicate that hail above 0.75 inch is not usually observed in the desert areas. They report that they have not experienced large hail or heard of damage due to hail. There are also no written records of damage due to hail in these areas.

Therefore, the hail size distribution given in Table 1 for Region III should be applied only to the mountainous areas of Region III. Except for the extreme northern end of Region III, any threat from hail to solar panels should be discounted. In the northern area there are reports of frequent, but usually small hail. Therefore, under normal circumstances it should pose no problem. It is possible, however, that some uninhabited areas have received larger hailstones.

C. Areal Density of Hailstones

Data on areal density of hailstones is generally not available. Most of the networks used heretofore for gathering data were dependent on volunteer observers. They were asked to record such information as stone size and storm duration, but there are few reports of areal density. One of the few, which is used here, is available in Ref. 5. A table is provided in this report of the maximum number of stones of a given diameter and the average number per square foot, based on a six year study. These data, from Ref. 5, were taken in Illinois and are summarized in Table 2.

The data were taken with hailpads. Since hailpads are usually one ft^2 in size and spacing of the hailpads in this study ranged from 3 miles apart to 275 feet, the areal density of only the smaller stones can be reasonably measured. Large stones are spaced far enough apart, so that areal density for them cannot really be measured in this way because of the small size of pad. The occurrence of the larger stones is poorly detected by the spacings used because of the small area over which they occur.

In order to obtain estimates of areal density for the larger stones, the cumulative fractional

Table 1. Cumulative probability of obtaining hailstones of a given diameter or greater*

Diameter, inches	Cumulative probability				
	Region I		Region II		Region III
	Upper limit	Lower limit	Upper limit	Lower limit	
≥0.25	0.94	0.50	1.0	0.88	0.58
≥0.50	0.75	0.20	0.96	0.58	0.14
≥0.75	0.46	0.085	0.65	0.30	0.075
≥1.00	0.26	0.030	0.40	0.15	0.05
≥1.25	0.15	0.006	0.25	0.06	
≥1.50	0.07	0.0012	0.16	0.017	
≥2.00	0.0008	0.00011	0.03	0.0017	
≥3.00	0.00025	4×10^{-6}	0.0013	0.00007	
≥4.00	0.00002	3.5×10^{-7}	0.0001	7×10^{-6}	

This table is obtained from the envelope curves in Figs. 3 and 4 and is to be used in conjunction with Fig. 2.

*Given that a hailstorm is occurring; data is based on hailpad and observer data.

Table 2. Number of hailstones per ft^2 (per hailfall, data taken in Illinois)

Time period	Average number of stones per hailfall (on 1 ft^2) for a given stone diameter, inches						Total
	1/8	1/4	1/2	3/4	1	>1	
1967-1968	100	14	12	2	1	0	129
1971-1972	79	11	7	0.9	0.1	0.04	98
1973-1974	105	14	4	0.4	0.1	0.01	123
Average 1967-1974	94.6	13.0	7.7	1.1	0.4	0.02	117
	Maximum number of stones per hailfall (on 1 ft^2) for a given stone diameter, inches						
1967-1968	1240	202	258	108	25	11	1844
1971-1972	1146	186	215	56	17	7	1627
1973-1974	1454	251	131	34	5	2	1877
Average 1967-1974	1280.0	213.0	201.3	66.0	15.7	6.7	1783

number of the total was plotted on log-log paper. This value was determined by taking the ratio of the number of stones per ft^2 (of a given diameter or greater) to the total number per ft^2 (all diameters). The number of stones per ft^2 was taken from Table 2. The ratio was then plotted versus hailstone diameter and the curve extrapolated to obtain the values for stones of diameters greater than 1 inch. This was done for both the average and the maximum number of stones per ft^2. Values of this ratio for large stones were taken from the curve and converted to number per ft^2. These are given in Table 3.

Since Table 3 represents the only data available it was used in the study discussed here. The values given in Table 3 represent two hail regimes. One is the average areal density expected on the basis of six years of data, which is a much milder environment than the maximum areal density. The recommendation here is to use the average density in Regions I and III (Fig. 2) as the representative of the hail environment expected there and the maximum density in Region III. One basis for dividing the country into these regions is observed hail damage. Hail damage is most intense in Region II which is subjected to severe hailstorms. The maximum density distribution seems to conform more to the reports associated with instances of large hail fall (Refs. 19 through 21) with the occurrence of widespread damage. For example, in the case of 2-inch hailstones, the maximum distribution gives one stone per 2 ft^2 and the average distribution gives one stone per 50 ft^2. The incidents of widespread damage were most probably caused by hail whose areal density was closer to the former than the latter number.

Table 3. Number of hailstones per hailfall of a given diameter or greater per ft^2

Diameter	Number of stones per ft^2	
	Average	Maximum
0.5	9.22	290.
0.75	1.52	88.
1.0	0.45	22.
1.5	0.064	2.1
2.0	0.019	0.45
3.0	0.003	0.05
4.0	0.0007	0.01

Secondly, as cited above, areal density values taken on 1-ft^2 pads separated by up to 3 miles could easily be underestimated or overestimated. Therefore, damage reports were given considerable weight in selecting the maximum areal density for use in Region II.

One final note, the use of the areal density distribution from Table 3 for Region III requires truncation for hailstones greater than 1 inch in order to conform with Table 2.

D. Duration of Hailstorms

The approach discussed makes use of parameters whose value has been integrated over the duration of a hailstorm. Therefore, the hailstone duration does not enter the calculations directly. Changnon (Ref. 1) cites averages of 10 minutes for hailstorms in Alberta (characteristics of area east of the Rockies into the Great Plains) and averages of 6.5 to 9.5 minutes in Illinois. Therefore, average duration of 5 to 10 minutes are to be expected with highs of up to 45 minutes.

III. DATA ANALYSIS

A. Probability Model

A probability model was developed for use in estimating the probability of impact by hailstones of a given size over a given period of time. The model is divided into several elements and makes use of three types of information about hailstones: the average annual number of hail days; the expected frequency distribution of hailstone sizes, given that a hailstorm has occurred and the areal density of hailstones. These three types of hail information are discussed in Sections II A, B, and C respectively. The values provided here are used in the probability model discussed here.

The first element of the model is the probability of obtaining a given number of hailstorms in a year. In this case the probability of occurrence of n hailstorms in a year is assumed to be given by a Poisson distribution. Gringorten uses this type of distribution (Ref. 22) in his report. A discussion of the use of this distribution to treat hail events appears in Refs. 23 and 24. The principal criterion for applying the Poisson distribution to an event, such as a hailstorm, is that the events be both comparatively rare and independent. In general, the mean number of days with hail (mean hail frequency) is small compared to the number of days in a year which comprise the hail season. Secondly, it is assumed here that no two storms which occur are dependent. This assumption may break down in areas with a large annual frequency of storm days. For instance, in the summer a series of storms associated with the passage of a single storm front may lead to hail occurrences which are not independent.

The Poisson distribution has a probability function given by the following:

$$f(n) = e^{-\lambda}\frac{\lambda^n}{n!} \qquad (1)$$

where n is the number of hail days in years (f(n) gives the probability of obtaining n hail days), and λ is the mean annual number of hail days.

It is often convenient to use what is called the distribution function given by:

$$F(N) = \sum_{n=0}^{N} f(n) \qquad (2)$$

where F(N) is the probability of obtaining N hail days or less in a year.

Thom (Ref. 23) discusses the use of the negative binomial distribution for those cases which are not adequately described by a Poisson distribution.

The reader is referred to Ref. 23 for a more detailed discussion of the negative binomial distribution.

Changnon and Schickendenz (Refs. 24 and 25) applied both distributions to hail occurrence data from Illinois and found a tendency for summer data to be fitted by the negative binomial distribution and the annual data to be fitted by the Poisson. This occurs because the summer data are more likely to be a series of dependent events (such as a series of storms), and hence, better represented by the negative binomial distribution which allows for dependence.

Based on these results and the greater simplicity of the Poisson distribution, it was used in the current study to determine the probability of obtaining N or less hail occurrences in a year. However, it must be emphasized that implicit in its use is the assumption of independence of events which may not always hold.

Use of Equations 1 and 2 gives the probability of obtaining N or less occurrences of hail in a given year:

$$\sum_{n=0}^{N} e^{-\lambda}\frac{\lambda^n}{n!}$$

In order to find the probability of obtaining hailstones of diameter d or larger the size frequency distribution given in Table 1 is used. In this case, since the parameter of interest is the probability of obtaining hailstones of a given size one or more times, the probability of obtaining hailstones of diameter less than d in each of N occurrences is determined. If the cumulative probabilities found in Table 1 are subtracted from 1, the probability of obtaining hailstones of diameter less than d, Q(d), is found. The value of N is selected sufficiently large so that additional terms which are omitted contribute insignificantly to the total probability; for this case N=20 is chosen. Therefore, the probability of obtaining hailstones of diameter d or greater in K years, P(d) is given by:

$$P(d) = 1 - \left[\sum_{n=0}^{20} e^{-\lambda}\frac{\lambda^n}{n!} Q^n(d)\right]^K \qquad (4)$$

The value of P(d) provides the probability of obtaining hailstones of a given diameter or larger over a period of time. However, this does not determine the actual probability of a hit in an area of a given size. In order to do so, the areal density of hailstones is required. The probability of being hit by a hailstone is given by a Poisson distribution. If the expected areal density of hailstones of a given diameter is M(d) (number of stones per unit area) the average number of hits on an area A is A M(d). The probability of getting at least one hit is given by:

$$1 - e^{-A\,M(d)} \qquad (6)$$

based on 1- probability of no hits.

The values of M(d) used here are taken from Table 3. The values under the average areal density are used to represent Regions I and III, and under the maximum areal density are used to represent Region II.

Therefore, the probability of a given fractional area, A, of a module being hit once or more by hailstones of diameter greater than or equal to d in K years is:

$$P(A,d) = \left\{1-\left[\sum_{n=0}^{20} e^{-\lambda}\frac{\lambda^n}{n!} Q^n(d)\right]^K\right\}\left(1-e^{-AM(d)}\right) \qquad (7)$$

Assume that a module consists of a number of areas, A_i, each of which is susceptible to damage from hits by hailstones of diameter d_i or larger. For instance, a cell may be subject to damage from direct hits by hailstones smaller than those which would cause damage if they struck a point over the substrate. Thus, a module of a given total area, A, can be divided into fractional areas A_i, each of which is susceptible to hailstones of a different size.

The risk of damage to a module from hail is dependent on the combined probability of each separate area being hit by hail of the size to which it is susceptible. This probability is given by:

$$P(A) = 1 - \prod_{i=1}^{\eta} \left[1 - P(A_i, d_i)\right] \qquad (8)$$

where η = total number of areas.

The mean time between hits, MTBH, is given by:

$$\text{MTBH} = -T/\ell n\,[1 - P(A)] \qquad (9)$$

where T is the time of observation and is equal to K in this case. This equation is adopted from Ref. 26 and derived from the concept of mean time between failure. In this case, the MTBH is an indication of time between hits by hailstones which could be damaging to a collector. For example, a MTBH of five years means that the mean time between successive hits of a collector by hailstones of a given size is five years.

B. Results of Applying the Probability Model to Hail Data

A sensitivity analysis was performed using the hailstone model given by Equations 7, 8, and 9 by varying the values of the probability of obtaining hailstones, Table 1, and the areal density of the hailstones. The quantity determined was the mean time between hits for a 20-year exposure for a panel 4 feet by 4 feet. The analysis was performed for one, three, five, and nine hailstorms per year, and hailstone sizes of 1, 1.5, 2 and 3 inches.

Samples of the results of the analysis are given in Figs. 5 and 6. In these figures, MTBH is plotted versus the probability of obtaining hailstones (given that a hailstorm has occurred). A separate curve is plotted for each of a given number of areal densities.

Areas of each set of curves were sectioned off, based on the probability of occurrence and areal density ranges, given in Tables 1 and 3, respectively, for a given size hailstone. For the purpose of this analysis, the entire 4 feet x 4 feet panel is assumed susceptible to damage from the same size hailstone. This simplification is required because of the large number of combinations or probability of occurrence and areal density which was used. This should not affect the results by an appreciable amount. The ranges result from use of the upper and lower values for probability of

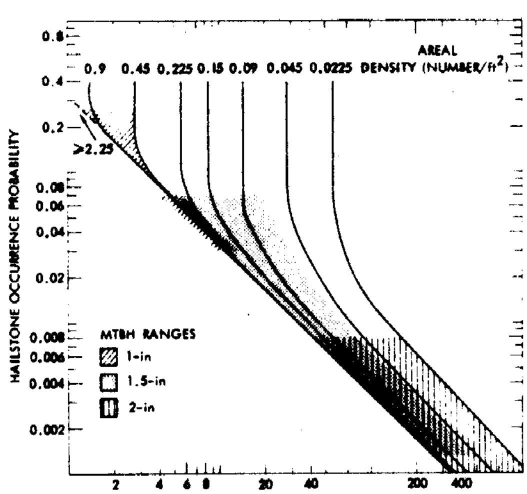

Fig. 5. Region I: MTBH vs probability of occurrence of hailstones of a given size for an area with three hailstorms/year assuming a 20-year exposure

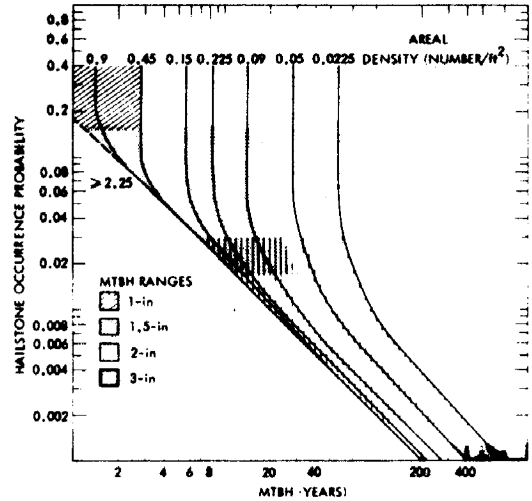

Fig. 6. Region II: MTBH vs probability of occurrence of hailstones of a given size for an area with five hailstorms/year assuming a 20-year exposure

occurrence and the average and maximum values for areal density. The range of values of MTBH for each hailstone size denotes the range of uncertainty for MTBH in the given geographical region. A value was also selected from the center of the range as the most probable value. The range of values for a given size of hailstone, is given for Regions I and II with the most probable value. Region III is represented by a single point since only one set of probability of occurrence and areal density values was considered appropriate.

The analysis of Region I was based on use of one and three hailstorms per year, and that Region II on three, five and nine hailstorms per year. Region III is based on one, three and five hailstorms per year, the latter value representing mainly mountainous areas in the northern part. The selection of annual number (range) of hailstorms for this phase of the analysis is based on the number of storms most prevalent for the region in question.

The sensitivity analysis indicates the MTBH is sensitive to the probability of occurrence and areal density in some range of values and insensitive to others.

The results of this phase of the analysis are summarized in Table 4 giving the ranges and most probable values. The MTBH are given for the appropriate region based on the annual number of hail days for selected hailstone diameters. A range of values plus an average or most probable value obtained by visual inspection of curves such as those given in Figs. 5 and 6 is provided. The following summary is obtained by considering Table 4. In Region I, 1-inch hailstones are responsible for MTBH less than 20 years; while 2-inch hailstones lead to MTBH greater than 20 years. In Region II, the MTBH for 1-inch hailstones is very short, while the MTBH for 2-inch hailstones spans a very large range. The lower end of the range presents MTBH for less than 20 years; however, the upper end presents MTBH well

Table 4. Mean time between hits for regions I, II, and III

Annual number of hail days	Hailstone size, inches	Region I MTBH, years		Region II MTBH, years		Region III MTBH, years
		Range	Average	Range	Average	
1	1	4 - 30	10			20
	1.5	15 - >1000	150			
	2	130 - ≥1000	500			
	3					
3	1	1.2 - 11	4	0 - 2.8	2	7
	1.5	5 - 460	50	2 - 42	12	
	2	40 - ≥1000	250	11 - 750	120	
	3			500 - ≥1000	≥1000	
5	1			0 - 2.8	2	4
	1.5			1.1 - 30	8	
	2			6.8 - 420	65	
	3			320 - ≥1000	≥1000	
9	1			0 - 2.8	1.7	
	1.5			0 - 25	6	
	2			3.6 - 240	35	
	3			170 - ≥1000	≥1000	

in excess of 20 years with the average larger than 20 years.

IV. CONCLUSIONS AND RECOMMENDATIONS

This report presents the data and approach used in a study to develop a hail environment for use with solar photovoltaic modules. The results are given in terms of the mean time between hits for a given region. The difficulty with taking a rather small amount of data and generalizing it to a large area is summed up by Changnon (Ref. 1, p. 626):

"Hail, whether it is viewed as the quickly melting hailstones on a patio, the hailstorms during one June week in Colorado, or the hail season in Alberta, exhibits enormous variability that exceeds that of most other weather conditions. This time and space variability is the key characteristic of hail, and the variability results because hail falls are such small scale areal phenomenon and relatively infrequent events at any one point."

Changnon commented further on the time variability (Ref. 27, p. 211):

"The temporal variation of these events is sufficiently great that accurate data for any particular 10- and 20-year period may provide a point average that is considerably above or below the true long term average for that point."

One can conclude that the results from a model such as that used here will overestimate the potential damage from hail in some areas and underestimate it in other areas.

Two aspects of the problem need further consideration. First, there are data available which have not been reduced. Reduction of these data would provide more information from which to determine size distribution for areas in which hail damage is a serious problem. The second aspect, and the most important to consider, is interpretation of the data that are reduced and nonreduced. This includes both data directly interpretable in terms of hail parameters and data which are indirectly interpretable. The first type consists of such things as hailstorm observations and hailstone size data; the second type consists of such things as observations of radar echoes. The ideal approach would be to correlate the first type of data where it exists, with the second. This is important since the first type exists for few locations, while the second type is available for more locations.

It is recommended that a study be initiated to cover those areas where hail presents a serious problem and where photovoltaic applications have a significant potential. The study should be conducted by personnel familiar with hail statistics and meteorological phenomenon. The special characteristic that is required is the ability to assess the data available and relate it to various meteorological and climatic conditions. In this way, hail models may be developed for specific locations affected by a given type of climatology. Also, meteorological observations which have been recorded can be statistically analyzed in order to develop a predictive model whose end objective is to provide an estimate of a given set of hail parameters for an area.

Therefore, any further studies performed to assign hail risk should be performed for a specific location, taking into account available records for hail and other meteorological parameters and prevailing meteorological, topographic and man-made influences.

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