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Wind, Earthquake, Snow, and Hail Loads on Solar Collectors

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The report describes and interprets wind-tunnel, full-scale, and field studies of wind and snow loads on flat plate solar collectors, conducted under contract for the National Bureau of Standards, and uses results of these studies and other data available in the literature to develop information, guidelines, and criteria for the design of flat plate collectors subjected to the action of wind, snow, and earthquake loads. Also given in the report are data on hail loads, based on information and studies available in the literature.

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ABSTRACT

The Report describes and interprets wind-tunnel, full-scale, and field studies of wind and snow loads on flat plate solar collectors, conducted under contract for the National Bureau of Standards, and uses results of these studies and other data available in the literature to develop information, guidelines, and criteria for the design of flat plate collectors subjected to the action of wind, snow, and earthquake loads. Also given in the report are data on hail loads, based on information and studies available in the literature.

PREFACE

This report is divided into four parts. Part I, entitled Wind Loads on Flat-Plate Solar Collectors presents performance requirements for flat-plate collectors subjected to wind loads and their supporting systems, and describes pending revisions to the specification of wind speeds in the American National Standard A58.1. A description, summary, and interpretation of recent wind tunnel and full-scale measurements of wind loads on flat plate collector systems, performed by Virginia Polytechnic Institute and State University under contract with the National Bureau of Standards, are presented. The approach employed to develop design criteria, based on these measurements is described. Wind load design criteria are presented in detail, and numerical examples are provided. Part II, entitled Earthquake Loads on Solar Collectors, examines the relative importance of seismic forces in the design of solar collector systems and shows that these forces ae generally small compared to those induced by wind. Information is provided on the design of solar collectors subjected to seismic loads. Part III, entitled Snow Design Criteria for Flat-Plate Collector Installations, presents performance requirements for flat plate collectors subjected to snow loads and their supporting systems, and describes findings of field studies conducted in 1979 under contract with the National Bureau of Standards. The approach employed to develop design criteria is described, and snow loading design criteria are presented in detail. Part IV, entitled Hail Loads on Solar Collectors, presents data on hail loads based upon information and studies available in the literature.

The report is primarily designed to be a source document for use by code and standard writing bodies in developing minimum design loads for solar collectors. For this reason, a fairly high level of complexity has been retained reflecting the influences of various pertinent factors. This is particularly true in the case of wind loads.

The authors have endeavored to link the guidelines and provisions suggested in this report to the proposed 1980 draft of the American National Standard A58.1 produced by the American National Standards Institute (ANSI). This draft, which is currently being balloted for adoption, contains numerous improvements over the 1972 version and it is expected that the draft will be adopted soon. Since the numbering of figures and tables in the final adopted version will differ from those in the draft (due to a format change), all figures and tables referenced in this report are referred to by name rather than by number.

The comments and cooperation of Mr. Robert Dikkers of the Center for Building Technology, NBS, and of Messrs. Tieleman, Akins, Sparks, O'Rourke, Corotis, Dowding, Rossow, and Changnon are gratefully acknowledged. Mr. Emil Simiu served as project leader.

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SI Conversion Units

Length

1 foot (ft) = .3048 meters (m)

1 inch (in) = 0.0254 meters (m)

1 mile (U.S. Statute) = 1.609347×10^{3} meters (m)

Velocity

1 mile per hour (mph) = 4.470400×10^{-1} meters per second (m/s)
= 1.609347 kilometers per hour (km/h)

Force

1 pound-force (lbf) = 4.448 newtons (n)

Pressure

1 pound-force per square foot (psf) = 47.880 pascals (Pa)

PART I

WIND LOADS ON FLAT-PLATE SOLAR COLLECTORS

by

Timothy A. Reinhold

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1. INTRODUCTION

Although extensive charts and tables have been developed for guidance in determining wind loads on buildings and other structures, the advent of solar collectors has led to many situations which are not adequately covered by existing wind load criteria. While it is reasonable to expect that roof wind loads are applicable for solar collectors mounted directly on a roof surface or for collectors which form the roof surface, no direct correspondence is apparent for many of the other common installation configurations. Consequently, a study of wind loads acting on typical solar collector installations was conducted using wind tunnel models and a full-scale installation. This report proposes specific design criteria which are based on recent experimental data reported in ref. 1 and on the 1980 draft revision of American National Standard A58.1, "Building Code Requirements for Minimum Design Loads in Buildings and Other Structures" (ANSI A58.1 - 1980/Draft) [2]*. The criteria provide for safety and serviceability requirements for solar collector cover plates, individual collectors and systems of collectors subjected to wind loads.

In order to design solar collector installations which meet specified performance requirements for wind loads, information is needed which prescribes wind loads on cover plates, individual collectors, arrays of collectors, and supporting systems. The prescription of wind loads requires knowledge of extreme wind speeds which can be expected at the site being considered and of appropriate pressure coefficients. Building codes and standards which consider wind loading generally include both classes of information, as well as the procedures for using that information to calculate wind loads. The approach followed herein was: (1) Update estimates of extreme winds for the ANSI A58.1 - 1980/Draft, (2) Obtain, from wind tunnel tests, additional data on pressure coefficients for use in the specification of wind loads on solar collectors, and (3) Develop specific guidelines for determining wind loads on solar collectors which use the ANSI A58.1 - 1980/Draft as a base document and which reflect the additional information obtained from the wind tunnel tests.

2. PERFORMANCE REQUIREMENTS

There are four basic requirements for the performance of solar collector installations under wind loads:

(a) SAFETY AND SERVICEABILITY OF SOLAR COLLECTOR COVER PLATES: Collector cover plates should not fracture due to wind loading and devices used for their attachment should withstand the wind loads.

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* Numbers in brackets indicate references at the end of each part.

(b) SAFETY OF INDIVIDUAL COLLECTORS: Individual collectors should not tear loose from their supports due to wind loads.

(c) SAFETY OF COLLECTOR SYSTEM SUPPORTS: Collector system supports should not collapse due to wind loading.

(d) SAFETY AND SERVICEABILITY OF BUILDING COMPONENTS SUPPORTING COLLECTOR SYSTEMS: Building components which support collector systems should not collapse or perform adversely due to the weight of the collector systems and induced wind effects.

Two other items are noted for consideration by the designer, although no specific provisions are developed. First, solar collector systems are often designed for a longer service life than most roof membrane systems. Consequently, care should be employed in designing the collector system to allow for expected service of the roof membrane. Second, investigations of damage caused by extreme winds have indicated that a significant amount of damage may be due to low-cycle fatigue. The state of the art does not adequately provide for the development of specific provisions for low-cycle fatigue at the present time. It is expected that low-cycle fatigue will not be a significant problem provided that components of solar collector systems are designed to withstand the prescribed loads without exceeding the allowable stresses conventionally used for the materials in question.

3. REVISIONS TO ANSI A58.1

This project provided partial support for two research efforts which contributed to the development of a new map for extreme wind speeds in the United States. The map is part of the proposed revisions to the ANSI A58.1 Standard, ANSI A58.1 - 1980/Draft. In the first study, extreme wind speeds caused by extratropical storms at over 100 primary weather stations in the United States were considered. A portion of the study was concerned with the selection of the best probability distribution to fit the historical data. These distributions were then used to predict the expected extreme wind speeds for a variety of return periods ranging from a few years to hundreds of years. Results are reported in ref. 3. The second study considered hurricane wind speeds along the Gulf and Atlantic coasts of the United States. Probability distributions of hurricane climatological characteristics, based on historical data, were used to simulate a large set of hurricanes using Monte Carlo techniques. Based on the simulated hurricanes, probability distributions of extreme wind speeds were developed for points at 50 nautical mile intervals along the Gulf and Atlantic coasts of the United States. Extreme wind speeds determined from the probability distributions are reported in ref. 4 for various return periods ranging from 10 years to hundreds of years. Extreme wind speeds predicted in these studies were used to develop an updated map which is included in the ANSI A58.1 - 1980/Draft.

4. THE VPI & SU EXPERIMENTAL INVESTIGATION

An experimental investigation was conducted for the National Bureau of Standards by Virginia Polytechnic Institute and State University (VPI & SU) during 1978-80 to determine wind loads on solar collector panels. The investigation involved both wind tunnel model tests and full-scale measurements. Descriptions of the buildings and solar collector configurations investigated in the model and full-scale tests are presented together with test results in a three volume report [1]. Also included are descriptions of the flow conditions, instrumentation, test methods and data reduction techniques. A brief summary of the test program, major findings and conclusions are presented in the following subsections.

4.1 TYPES OF INSTALLATIONS CONSIDERED

The model tests were designed to include a cross section of typical installations. The model configurations can be roughly grouped as roof installations on low rise buildings and ground installations. Roof installations are further grouped according to whether collectors are mounted on sloped or flat roofs. These two types of roof installations are illustrated in figures 1 and 2, respectively. Ground installations are grouped according to whether collectors are placed against a wall (berm units) as shown in figure 3, or whether they are placed in the open, away from buildings, as shown in figure 4.

As can be seen in figures 1 through 4, the number of parameters required to describe the various configurations is quite large. Consequently, it was not possible to run an exhaustive series of tests where all parameters were varied independently. Instead, a series of representative cases were investigated involving some 63 configurations and well over 1500 individual tests. The roof overhang and the length to width ratio of model buildings (see figure 1) were not varied systematically because earlier investigations [5,6] indicated that roof pressures were not significantly influenced by variations in these building characteristics.

Tests of collector installations on buildings with sloped roofs included cases where the collectors were mounted directly on the roof surface, mounted parallel to the roof surface but with an open gap between the roof and the back of the collector, and mounted at an angle to the roof surface. Such configurations are described by the parameters shown in figure 1.

Tests of collector installations on buildings with flat roofs, figure 2, included cases where the collectors were mounted with various angles of inclination to the roof. Tests were conducted on models with and without parapets. Parapet cases included vertical parapets, $\beta = 90°$, and inclined parapets, $\beta = 60°$. Installations with multiple rows of collectors were also studied.

Berm unit tests, figure 3, included a single row of collectors mounted against a building wall. One and two story buildings with flat or sloped roofs were used in the tests. The collector array was mounted at various angles of inclination to the horizontal.

Solar collector systems consisting of single or multiple rows were included in the tests of general ground installations, figure 4. The collector arrays were mounted at various angles of inclination to the horizontal.

4.2 WIND TUNNEL MODELING OF SOLAR COLLECTOR INSTALLATIONS AND SIMULATION OF FLOW

The buildings and solar panels were modeled in the wind tunnel at a geometric scale ratio of 1/24. This scale ratio was chosen in order to provide models which would be large enough to facilitate pressure measurements and also to reduce the possibility that the pressure coefficients would experience Reynolds number dependence [1]. However, the wind tunnel flow was originally designed for use in testing tall buildings at a model scale of 1/400 to 1/600. For the testing of low-rise buildings, emphasis is placed on modeling the lower portion of the boundary layer. Thus, if the ratio of turbulence integral length scales for model and prototype is considered at roof elevation, the proper geometric scale ratio is probably on the order of 1/200 to 1/300. This results in a discrepancy by a factor of about 10 between the geometric scale of the structural model and the geometric scale of the longitudinal component of turbulence.

With regard to the discrepancy between model scale and scale of the longitudinal component of turbulence, the ANSI A58.1 - 1980/Draft states that wind tunnel tests will be considered properly conducted only if:

> "The geometric scale of the structural model is not more than three times the geometric scale of the longitudinal component of turbulence."

It is clear that these model tests would not satisfy this criterion. On the other hand, the ANSI A58.1 - 1980/Draft also notes that due regard should be given to the dependence of pressures on Reynolds number. Consequently, while the tests do not fit the scaling requirements of ANSI A58.1-1980/Draft, the results would have been questionable because of possible Reynolds number dependence if the scaling requirements had been satisfied for the given flow conditions.

The scaling requirements in the ANSI A58.1 - 1980/Draft for acceptable wind tunnel tests can probably be considered conservative. The current state of the art of wind tunnel testing does not allow a clear assessment of the consequences of discrepancies in modeling velocity profiles, turbulence intensity profiles, or geometric scales, especially when such discrepancies occur simultaneously for several of these parameters.

There are indications that correct modeling of the intensity of the turbulence is one of the most important considerations [5,7]. Furthermore, comparisons of wind tunnel and full-scale results would suggest that point pressures can be adequately reproduced in the wind tunnel provided that the scale of the longitudinal turbulence component is at least as large as the largest model dimension [5].

In the experimental investigation of wind loads on solar collectors, the length scale of the longitudinal turbulence component was 2.5 to 3.0 times as large as the length of a collector [1] but was smaller than the largest building dimension or the length of a row of collectors. Furthermore, the pressures reported are averaged over given areas (as opposed to point pressures). Area averaged loads or pressures were chosen rather than point pressures and corresponding loads because it was felt that the area averaged pressures more closely represented loads on collector panels or their supports. The effects of distortions in the scales are likely to be more pronounced for area averaged pressures than for point pressures. However, as mentioned previously, the effects of the distortions cannot presently be quantified.

Two possible solutions to this dilemma are available. The first is to compare model test results with those obtained from full-scale tests. The second is to compare results for collectors mounted flat on a roof with design values for roof loads which have been shown by other tests and past experience to be adequate. This second solution represents essentially a calibration of the test results to current practice. Both solutions have been pursued and will be discussed in the following sections.

Other features of the flow simulation are described in ref. 1. The flow is considered to compare favorably with that of Exposure Category B in ANSI A58.1-1980/Draft. This is based primarily on a comparison of turbulence intensities of the simulated flow at model roof height with expected intensities for full-scale exposure conditions. The mean velocity profile actually corresponded more to a profile characteristic of Exposure A than Exposure B since the power law exponent was 0.37 for the wind tunnel flow. However, as noted earlier, the intensity of the turbulence is considered to be a more important parameter to be simulated. Furthermore, normalization of pressures by means of local velocity pressures (as was done in this work [1]) tends to remove the dependence of pressure coefficients on the mean velocity profile.

4.3 COMPARISON OF VPI & SU MODEL RESULTS WITH FULL-SCALE TEST RESULTS AND OTHER MODEL TEST RESULTS

4.3.1 General

Evaluation of wind tunnel model tests must always center upon questions concerning how well the model results reproduce full-scale conditions. The answers to such questions ultimately depend upon comparisons of model and full-scale test results, although some insights can be obtained from comparisons of different model studies. For these reasons, the test program included a series of full-scale tests conducted at the VPI & SU Price's Fork Research Station, and model tests of the Price's Fork building and solar collectors. Additional tests were conducted on a model of the full-scale experimental house at Aylesbury, England for which extensive full-scale and other model test results are available. Consequently, it has been possible to conduct comparative studies of model and full-scale tests on the Price's Fork building and on the Aylesbury building. In addition it has been possible to compare results obtained from model tests conducted at VPI & SU and at the University of Western Ontario (UWO) to assess effects of differences in model scales and flow simulation. These comparisons are presented in detail in ref. 1 and 8 and will be summarized in subsections 4.3.2 and 4.3.3.

4.3.2 Comparison of Price's Fork Model and Full-Scale Test Results

It is noted that the conclusions that can be drawn from the comparison between model and full-scale tests should not be regarded as definitive, owing primarily to the following basic difficulties. First, it was not possible in this project to reproduce the topographic features of the terrain surrounding the full-scale site. The actual site, although typical of many possible sites, differed significantly from the uniform, homogeneous terrain used in the laboratory simulation. Second, while the procedure for estimating peak loads adopted in ref. 1 to compensate for filtering problems in the original tests was satisfactory on the average, there were individual situations where estimates based on the procedure deviated significantly from the actual peak loads. One of these situations consists precisely of the Price's Fork model. The deviations in this case are shown in tables 1 and 2. Owing to the factors mentioned above, judgement should be used in attempting to draw conclusions from the comparisons between model and full-scale measurements on the Price's Fork configuration.

Based on comparisons of model and full-scale test results, the following conclusions were drawn in ref. 1:

> "For nearly stationary data records local mean pressure coefficients agree reasonably well, while local rms pressure coefficients and the magnitude of local peak pressure coefficients are approximately twice as large for the full-scale."

These conclusions are suggested for both pressures on a single face of a collector and net pressures on a collector. On the other hand, the comparison of model and full-scale results shown in tables 1 and 2 suggest different conclusions which are listed below. The pressure coefficients presented in tables 1 and 2 are based on mean hourly wind speeds as opposed to fastest mile wind speeds which are used by ANSI A58.1-1980/Draft.

(1) Coefficients shown in table 1.a indicate that the full-scale peak coefficients for negative pressures are usually 1.5 to 2.0 times larger than corresponding coefficients for predicted peaks based on the model test results.

(2) Comparison of coefficients listed in table 1.b indicates that model and full-scale results are essentially equal for wind directions of 0 and 360 degrees where the mean pressure was also positive. The coefficients also agree within experimental scatter for the other wind directions listed, where the mean pressure was negative. The probability distribution of positive peaks for cases where the mean pressure is negative has not been studied [1].

(3) Coefficients for peak net negative pressures shown in table 2.a indicate a significant discrepancy between predicted and measured peak values for the model tests. The predicted peaks from the model tests are generally equal to or larger than the peak coefficients obtained from full-scale measurements.

(4) Coefficients for peak net positive pressures shown in table 2.b indicate the same conclusions listed above under item 3.

Consequently, while the comparison of model and full-scale results presented in ref. 1 might suggest that model coefficients for peak pressures (both for a single face and net on a collector) should be doubled, the comparison shown in tables 1 and 2 would suggest that predicted net pressures should not be increased. Owing to the discrepancies illustrated it is difficult to suggest any systematic corrections to the coefficients obtained from the wind tunnel tests.

4.3.3 Comparison of Aylesbury Full-Scale and Model Test Results

A detailed three-way comparison between full-scale pressure measurements on a two-story building at Aylesbury, England, and pressure measurements on models of the Aylesbury building which were conducted separately at VPI & SU and UWO are contained in ref. 8. Based on that comparison, ref. 8 suggests the following conclusions:

"... that model mean, rms and peak pressure coefficients are generally in agreement with full-scale results if:

(1) Local pressure coefficients are used.

(2) The streamwise turbulence intensity is modeled adequately for at least two building heights.

(3) The streamwise turbulence integral scale is at least as large as the largest model dimension.

(4) Gross features of the upstream terrain such as mountain ridges and changes in nearby surface elevation are modeled adequately.

(5) The full-scale data records do not exhibit a nonstationary character such as low-frequency components and/or short-duration gusts."

There are several facts which preclude the use of these conclusions to justify the numerical values of pressure coefficients for solar collectors as measured in the wind tunnel tests. First, the VPI & SU model of the Aylesbury building was constructed at a 1/50 scale rather than the 1/24 scale used in the solar collector tests. As a result of this scaling, the longitudinal turbulence integral length scale was at least as large as the largest model dimension. As noted previously, the integral length scale in the solar collector tests was larger than the length of a collector but not larger than the largest model dimension or the length of an array of collectors. Second, only point pressures are considered in the comparison of the Aylesbury building and the appropriate model tests. Consequently, it is speculative to apply these same conclusions to the solar collector work where area averaged pressures were measured.

4.4 COMPARISON OF MODEL RESULTS WITH ANSI A58.1-1980/DRAFT PROVISIONS

Since neither of the comparisons of model versus full-scale test results proved completely satisfactory in resolving questions about the model test results, it is important to compare the model results against what is used or specified in current practice. The ANSI A58.1 wind load provisions are a logical benchmark for comparison since the provisions have a historical basis which suggests that they are adequate. Several of the solar collector installations included collectors mounted flat on the building roof and it is reasonable to compare the cover plate pressure coefficients with ANSI A58.1 roof pressure coefficients for similar slopes. Rather than use the 1972 edition of ANSI A58.1, which is the latest adopted version of the standard, it was decided to compare pressures with ANSI A58.1 - 1980/Draft because it includes advances in the state-of-the-art of wind load definition and because it is expected to be adopted in the near future without substantial changes.

A comparison of cover plate pressure coefficients and ANSI A58.1-1980/Draft roof pressure coefficients is shown in table 3. In the comparison, if a collector was located in more than one zone it was assumed to be located in the higher zone if more than 30 percent of its area projected on the roof fell in the higher zone. As a result, the end collectors on the Price's Fork building are located in zone 2 (see ANSI A58.1-1980/Draft) since they are placed near the edge of the roof. On the other hand, the solar collector arrays on the other model buildings were shorter than the length of the building and consequently the end collector was some distance away from the roof edge.

All coefficients presented in table 3 are for use with fastest mile wind speeds since that is the usual ANSI convention. However, the ANSI A58.1-1980/Draft coefficients are intended for use with Exposure C wind speeds while the model conditions are believed to correspond more closely to Exposure B conditions. Based on comparisons of wind pressures and pressure coefficients reported in ref. 6, it can be shown that peak pressure coefficients for Exposure B are as much as 1.5 to more than 2.0 times higher than peak pressure coefficients for Exposure C conditions. However, owing to the reduced wind velocities at low elevations for Exposure B conditions as compared to Exposure C, the design pressures for Exposure B are actually equal to or slightly lower than those for Exposure C. Consequently, the peak pressure coefficients obtained in the model tests should be about 1.5 to 2.0 times larger than the ANSI A58.1-1980/Draft values.

In general, the values of the model and ANSI coefficients presented in table 3 are comparable. This is not consistent with the expected results as outlined in the previous paragraph. It can therefore be concluded that the peak surface pressures measured in the wind tunnel are between about 1.5 and more than 2.0 times lower than the surface pressures specified in current design practice.

5. DEVELOPMENT OF DESIGN CRITERIA

The first consideration in developing design criteria which would reflect the information obtained from the VPI & SU wind tunnel tests was to decide what corrections if any should be made to the pressure coefficients. Based on the comparisons with the full-scale measurements and with ANSI A58.1-1980/Draft provisions it was concluded that use of the pressure coefficients obtained from the wind tunnel tests with wind speeds for Exposure B would yield design pressures which would be unrealistically low, whereas their use with wind velocities for Exposure C would provide reasonable design pressures. The correction, which amounts to an increase in the pressure coefficient of between about 1.5 to 2.0 times the wind tunnel value, is consistent with the correction suggested by some of the full-scale data.

The second consideration in developing the design criteria was to make the criteria compatible with the provisions of ANSI A58.1-1980/Draft. In the course of developing the guidelines for use with ANSI A58.1-1980/Draft an effort was made to use the ANSI tables as much as possible. This effort produced several relationships which are intuitively appealing. For example, as the collector is mounted at angles of inclination to the roof slope, the collector array begins to act as a roof ridge and it would naturally be expected that the end collector would experience pressures more nearly characteristic of zone 2 than zone 1 (as defined in table 3 and figure 1) even though the end collector might be well away from the edge of the roof. This trend did appear in the data. Consequently, the guidelines for determining pressures on end collectors when the collectors are mounted on sloped roofs at an angle of inclination to the roof, suggest that the end collector be designed for zone 2 pressures even if it lies within roof zone 1. A second interesting trend is that when the collectors protrude above the roof ridge, the peak pressures on end collectors tend to increase abruptly when more than half of the collector extends above the ridge height. This abrupt change occurred in the negative peak pressures on the cover plate and negative net loads, and corresponded to winds blowing over the roof ridge diagonally from the rear, i.e., since collectors face south, winds from the Northwest or Northeast directions. This trend could be explained by the effect of the accelerated flow over the roof that would begin to strike the upper part of the collector.

Reductions in pressures for collectors that account for trends such as those discussed above are reflected in the guidelines suggested in section 6. In some cases the trends are based on only a few data points but their consistency and the fact that most could be explained intuitively led to the conclusion that the guidelines should include provisions to account for the variations in pressure coefficients. It is recognized that design of many installations may not warrant use of the detailed reductions in pressure coefficients presented. In those cases the designer should simply ignore the allowed reductions. It is also noted that if uniform strength is desired, all collectors should be designed to resist the pressures specified for end collectors.

It is recognized that manufacturers may want to design collectors or collector cover plates that can be used in any type of installation in certain geographical areas. It is possible to use the guidelines presented in section 6 to define broad categories by selecting the worst pressure coefficients for certain types of installations. Then knowing the design pressure for which the cover plate is certified, it is possible to establish limits on allowable wind speeds. An example of the application of this approach is presented in section 7.

6. WIND LOAD DESIGN CRITERIA

6.1 GENERAL

Recommended provisions for the determination of wind loads on solar collector cover plates, individual collectors, and systems of collectors are described in the following sections. The provisions are presented in the form of criteria followed by specific guidelines for using tables contained in ANSI A58.1-1980/Draft to obtain wind loads. Use of these wind loads in the design process will lead to systems which meet the criteria of sections 6.2, 6.3, 6.4, and 6.5.

6.1.1 Definitions

The following definitions apply to the provisions for wind loads on solar collector systems and system components.

DESIGN PRESSURE ON COVER PLATE, p - equivalent static pressure to be used in the determination of wind loads for solar collector cover plates. The pressure is assumed to act normal to the surface, either as a pressure directed toward the surface or as a suction directed away from the surface. A positive value of a pressure coefficient indicates a pressure directed toward the surface; a negative value indicates a suction.

DESIGN PRESSURE ON AN INDIVIDUAL COLLECTOR, p_N - equivalent static pressure to be used in the determination of wind loads for supports of individual solar collector panels. The pressure is assumed to act uniformly over the surface of the collector and in either direction normal to the plane of the collector. A positive pressure is one directed toward the surface with the cover plate; a negative pressure is one directed away from the surface with the cover plate.

DESIGN PRESSURE ON A SYSTEM OF COLLECTORS, p_{NS} - equivalent static pressure to be used in the determination of wind loads for supports of an array of solar collector panels. The pressure is assumed to act uniformly over the surface of the collector array and in either direction normal to the plane of the array. The design pressure is the largest of the negative or positive pressures acting in either direction normal to the plane of the collectors.

ZONE IN WHICH A COLLECTOR IS LOCATED - a collector mounted on a roof or against a wall is considered to be located in a designated zone if 70 percent or more of its area, projected on the roof or wall, falls within that zone. If a collector is located in more than one zone, it is assumed to be located in the highest zone where more than 30 percent of its projected area is located. The projection is taken normal to the plane of the roof or wall. The various zones on a roof or a wall correspond to the areas indicated in the table, "External Pressure Coefficients for Loads on Building Components and Cladding" of ANSI A58.1-1980/Draft.

6.1.2 Symbols and Notations

The following symbols and notations apply to the provisions for wind loads on solar collector systems and system components. Symbols which apply to collector installations are further illustrated in figures 1 through 4.

a: Distance from edge of roof or wall defining boundary between pressure zones and equal to 10 percent of minimum building width or 0.4 h, whichever is smaller, but not less than either 4 percent of minimum width or 3 ft, ft

A: Tributary area, sq ft

A': Fraction of collector area extending above roof ridge = $h_2/\ell \sin(\theta + \beta)$

B: Width of solar collector row, ft

$C_{i,j}$: j^{th} collector in i^{th} row of collectors

D: Horizontal center to center spacing between rows of collectors in multiple row installations, ft

GC_p: Pressure coefficient to be used in determining wind loads on solar collector cover plates

GC_{pN}: Pressure coefficient to be used in determining wind loads on individual solar collector panels

GC_{pNS}: Pressure coefficient to be used in determining wind loads on a row of solar collector panels

GC_{pi}: Internal pressure coefficient to be used in determining wind loads on solar collector panels or components

h: Average height of roof, equal to ridge height plus eave height divided by 2.0, ft

h_1: Reference height for velocity pressure to be used with pressure coefficients: (1) For roof installations h_1 = mean height of collector (see figures 1 and 2); (2) For berm units h_1 = mean roof height (see figure 3); (3) For other ground installations h_1 = top edge of collector (see figure 4), ft

h_2: Vertical distance between roof ridge and highest edge of collector (see figure 1) extending above ridge, ft

H: Parapet height above roof level, ft

I: Importance factor

K_z: Velocity pressure exposure coefficient at height z for terrain exposure C obtained from table with same name in ANSI A58.1 - 1980/Draft

ℓ: Length of collector, ft

p: Design pressure to be used in determining wind loads on solar collector cover plates, psf

p_N: Design pressure to be used in determining wind loads on individual solar collector panels, psf

p_{NS}: Design pressure to be used in determining wind loads on an array of solar collector panels, psf

q: Velocity pressure, psf

q_{h_1}: Velocity pressure evaluated at height $z = h_1$, psf

S: Spacing between roof and nearest edge of collector (measured perpendicular to roof - see figures 1 and 2) or spacing between ground and nearest edge of collector for ground installations (see figure 4), ft

V: Basic wind speed from map with same name in ANSI A58.1 - 1980/Draft, mph

w: Width of individual solar collector, ft

z: Height above ground level used in ANSI A58.1 - 1980/Draft and equal to h_1, ft

β: Angle of inclination of solar collector relative to roof slope for roof mounted collectors and relative to ground for ground mounted collectors.

ϕ: Slope of parapet measured from horizontal, degrees

θ: Slope of roof, degrees

(1): Zone 1 for wind loads on central portions of flat or sloped roofs; after ANSI A58.1-1980/Draft (see figures 1 and 2)

(2): Zone 2 for wind loads on edges of flat or sloped roofs; after ANSI A58.1-1980/Draft (see figures 1 and 2)

(3): Zone 3 for wind loads on corners of flat or sloped roofs; after ANSI A58.1-1980/Draft (see figures 1 and 2)

(4): Zone 4 for wind loads on central portions of walls of buildings; after ANSI A58.1-1980/Draft (see figure 3)

(5): Zone 5 for wind loads on end portions of walls of buildings; after ANSI A58.1-1980/Draft (see figure 3)

6.1.3 Warnings: Limitations of Data Base

A. Multiple Row Installations

The tested configurations of multiple row collector installations included only cases where the system formed a rectangle, i.e., no lateral offset between rows in a direction parallel to the rows. Consequently, no reductions in loads should be taken for systems which do contain lateral offsets.

B. Berm Units

The berm configurations tested included only cases where the collector array was shorter than the building wall on which they were located. The peak loads may increase significantly on the cover plates, individual collectors and on the system as a whole if the array protrudes past or above the wall of the building.

C. Arrays on Sloped Roofs

(1) Collector arrays which are not parallel to roof ridge

The tested configurations of collectors on sloped roofs included only cases where the array was parallel to the roof ridge. Consequently the coefficients developed apply only to these cases. However, it is conceiveable that in some installations on existing structures, which do not have a roof slope with a southern exposure, the collectors will be oriented in arrays of 1 or 2 collectors skewed with respect to the ridge. Caution should be employed in designing cover plates and support systems for collectors which are mounted in such a skewed fashion.

(2) Collectors mounted on the northern slope of a roof

It is conceivable that a row of collectors could be placed on the northern slope. No such configurations were tested in the wind tunnel and the pressure coefficients provided in the criteria do not apply to such installations. Wind loads on the cover plates and on the collectors may be greatly increased for such installations and caution should be employed in designing such systems and their supports.

(3) Collectors mounted on hip roofs

No tests were conducted using collector arrays on hip roof buildings. However, it is considered appropriate to assume the same pressure coefficients for arrays on hip roofs as are used on gabled roofs provided that the end collectors do not extend laterally past the end of the roof ridge. If the end collector does extend past the end of the ridge, this condition should be considered similar to that of the collector extending above the ridge roof, so that the collector should also be considered to be in zone 2.

6.1.4 Analytical Procedure

It is recommended that design wind pressures for SOLAR COLLECTOR COVER PLATES, INDIVIDUAL COLLECTOR UNITS, and ARRAYS OF COLLECTORS be determined in accordance with the appropriate equations, given in sections 6.2, 6.3 and 6.4 respectively, using the following procedure:

(1) Select the appropriate VELOCITY PRESSURE EXPOSURE COEFFICIENT, K_z, for height above ground h_1 and Exposure C from the table in ANSI A58.1-1980/Draft.

(2) Determine the appropriate IMPORTANCE FACTOR, I, from the table in ANSI A58.1-1980/Draft. Importance factors for Category I structures shall be used for determining the velocity pressure in the equations for sections 6.3 and 6.4 of this document. For velocity pressures used in the design of cover plates, section 6.2, importance factors corresponding to Category IV structures shall be used.

(3) Determine the basic wind speed for the site in question using the BASIC WIND SPEED MAP contained in ANSI A58.1-1980/Draft.

(4) Calculate the velocity pressure q_z for height h_1 using the equation given in the section on VELOCITY PRESSURE in ANSI A58.1-1980/Draft.

6.2 WIND LOADS ON SOLAR COLLECTOR COVER PLATES - SAFETY AND SERVICEABILITY REQUIREMENTS

CRITERION: Cover plates for flat plate solar collector systems and the devices used for their attachment shall withstand the wind loads based on the following analytical procedure and guidelines without exceeding the allowable stresses that are conventionally used for the material in question.

RECOMMENDED ANALYTICAL PROCEDURE: Wind pressures for use in the design of solar collector cover plates shall be determined in accordance with the following equation:

$$p = q_{h_1}(GC_p) - q_{h_1}(GC_{pi})$$

where $GC_{pi} = \pm\ 0.25$, whichever creates the worst loading case.

GC_p is obtained from the ANSI A58.1-1980/Draft table "External Pressure Coefficients for Loads on Building Components and Claddings for Buildings with Roof Height $h \leq 60$ ft", using the following guidelines.

GUIDELINES FOR USING ANSI A58.1-1980/DRAFT TO OBTAIN PRESSURE COEFFICIENTS FOR SOLAR COLLECTOR COVER PLATES:

I. Collectors Mounted on Sloped Roofs, $\theta > 10°$ 1/ - (see figure 1)

A. Collectors parallel to roof slope, $\beta \approx 0°$

1. Pressure directed toward the cover plate surface (positive pressures)

For any collector in an array, use GC_p corresponding to the positive pressures given for $30° < \theta \leq 45°$.

2. Pressures directed away from the cover plate surface (suctions - use negative values in tables)

(a) For end collectors in an array or individual collector systems:

Use GC_p corresponding to angle θ and the roof zone in which the collector is located

(b) For interior collectors in an array:

Use GC_p corresponding to angle θ and zone 1

B. Collectors inclined to the roof slope, $\beta > 0°$

1. Pressures directed toward the cover plate surface (positive pressures)

For any collector in an array, use GC_p (corresponding to the positive pressures given for $30° < \theta \leq 45°$)

2. Pressures directed away from the cover plate surface (suctions - use negative values in tables)

(a) For end collectors in an array or individual collector systems:

$GC_p = GC_p$ for angle θ and zone 2

where $\theta < 20°$, use values from table for $10° \geq \theta \geq 0°$.

1/ For roof slopes in excess of 45°, use values for 45°.

For A' > 0.5; $GC_p = GC_p - 0.5$[1]

EXCEPTION: For A' < 0.1, use GC_p corresponding to the angle θ and the roof zone in which the collector is located.

(b) For interior collectors in an array:

Use GC_p corresponding to zone 2 negative values given for $30° < \theta \leq 45°$

EXCEPTION: For A' < 0.1, use GC_p corresponding to the angle θ and roof zone 1

II. Collectors Mounted on Flat Roofs, $\theta \leq 10°$ - (see figure 2)

A. Basic cover plate loads for collectors on flat roofs

1. Pressures directed toward the cover plate surface (positive pressures)

For any collector in an array, obtain the magnitude of GC_p from the table values for zone 1.

$GC_p = -[GC_p \text{ for zone } 1]$

2. Pressures directed away from the cover plate surface (suctions - use negative values in tables)

a. For end collectors in an array or individual collector systems:

$GC_p = 1.2[GC_p \text{ for zone } 2]$

$GC_p = 1.2[GC_p \text{ for zone } 2] - 0.5$[1] of S > 0

b. For interior collectors in an array:

$GC_p = 1.1[GC_p \text{ for zone } 1]$

B. Flat roofs with parapets - allowable reductions to basic cover plate loads

---

[1] Note that GC_p for suction pressures is a negative number.

Suction pressure coefficients on cover plates for end collectors in an array or for individual collector systems may be reduced as follows:

$$GC_p = [GC_p \text{ from } 6.2\text{-II.A.2.a}]\ \{1.0 - [3(H-S)/\ell \sin\beta]\}$$

but the magnitude of GC_p shall not be less than GC_p for zone 1.

C. Multiple rows of collectors on flat roofs - (no lateral offset between rows in direction parallel to rows) - provided $D < 2.5\ \ell$: see figure 2

Negative pressure coefficients (suctions) on cover plates for end collectors in an array may be reduced as follows:

1. For end collectors on interior rows:

$$GC_p = [GC_p \text{ from sec. } 6.2\text{-II.A.2.a}][1.0-(\frac{90-\beta}{15})(0.15)]$$

but the magnitude of GC_p shall not be less than GC_p for zone 1.

2. For end collectors on last row - (see figure 2):

$$GC_p = [GC_p \text{ from sec. } 6.2\text{-II.A.2.a}][1.0-(\frac{90-\beta}{15})(0.10)]$$

but the magnitude of GC_p shall not be less than GC_p for zone 1.

III. Collectors Mounted on Ground Installations

A. Collectors placed next to a building wall - berm units (see figure 3)

1. Pressures directed toward the cover plate surface (positive pressures)

For any collector in an array, use GC_p corresponding to the positive pressures given for walls. Note that the values in the table apply for zones 4 and 5.

2. Pressures directed away from the cover plate surface (suctions - use negative values in tables)

Use GC_p corresponding to the negative pressure given for walls and the appropriate wall zone.

B. Single row of collectors mounted close to ground and not leaning against a building.

1. Pressures directed toward the cover plate surface (positive pressures)

   For any collector in an array use GC_p corresponding to the positive pressures given for walls. Note that the values in the table apply for zones 4 and 5.

2. Pressures directed away from the cover plate surface (suctions - use negative values in tables)

   (a) For end collectors in an array or individual collector systems.

   Use GC_p corresponding to wall pressures in zone 5.

   (b) For interior collectors in an array

   Use GC_p corresponding to wall pressures in zone 4.

C. Multiple rows of collectors mounted close to ground and not leaning against a building (no lateral offset between rows in direction parallel to rows) provided $D < 2.5\ \ell$: see figure 4.

Pressure coefficients on cover plates are obtained using the guidelines in section 6.2 - III.B and may be reduced as follows:

1. For collectors in interior rows:

   $$GC_p = [GC_p \text{ from sec. 6.2-III.B}][1.0 - (\frac{90-\beta}{15})(0.15)]$$

   but the magnitude of GC_p shall not be taken less than 40 percent of the unreduced value of GC_p.

2. For collectors in the last row - (see figure 4):

   $$GC_p = [GC_p \text{ from sec. 6.2-III.B}][1.0 - (\frac{90-\beta}{15})(0.10)]$$

   but the magnitude of GC_p shall not be taken less than 60 percent of the unreduced value of GC_p.

6.3 WIND LOADS ON INDIVIDUAL COLLECTORS - SAFETY REQUIREMENTS

CRITERION: Support brackets for individual flat plate solar collectors shall withstand the wind loads based on the following analytical procedure and guidelines without exceeding the allowable stresses that are conventionally used for the material in question.

ANALYTICAL PROCEDURE: Design wind pressures for individual collector panels to be used in determining net loads on individual collectors shall be determined in accordance with the appropriate following equation:

A. For collectors which are not an integral part of the roof, i.e. are placed on top of the roof or are actually separate from the roof surface

$$p_N = q_{h_1} (GC_{PN})$$

B. For collectors which are an integral part of roof, i.e., such that their back surface is effected by the internal pressure of the building

$$p_N = q_{h_1} (GC_{PN}) - q_{h_1}(GC_{Pi})$$

where: $GC_{Pi} = \pm\ 0.25$, whichever creates the worst loading case.

GC_{PN} is equal to GC_P as given in the ANSI A58.1-1980/Draft table, "External Pressure Coefficients for Loads on Building Components and Cladding for Buildings with Height $h \leq 60$ ft", using the following guidelines.

NOTE: Obtain GC_P from the negative values in the tables but recognize that the loads can act in either direction normal to the collector.

GUIDELINES FOR USING ANSI A58.1-1980/DRAFT TO OBTAIN NET PRESSURE COEFFICIENTS FOR INDIVIDUAL SOLAR COLLECTORS:

I. Collectors Mounted on Sloped Roofs, $\theta > 10°$ 1/ (see figure 1)

A. For collectors parallel to roof slope, $\beta \simeq 0°$:

$CG_{PN} = \pm$ [GC_P for the angle θ and the appropriate zone]

$GC_{PN} = \pm\ [GC_{PN} - 0.5]$ if $S > 0$ 2/

1/ For roof slopes in excess of 45°, use values for 45°.

2/ Note that GC_{PN} used for net loads is a negative number.

B. Collectors inclined to the roof slope $\beta > 0°$

1. For end collectors in an array or individual collector systems:

$GC_{PN} = \pm$ [GC_p for angle θ and zone 2]

$GC_{PN} = \pm [GC_{PN} - 0.5]$ if $A' > 0.5$[1/]

$GC_{PN} = \pm [GC_{PN} - 0.5]$ if $S > 0$[1/]

Note: $GC_{PN} = \pm [GC_{PN} - 1.0]$ if $A' > 0.5$ and $S > 0$[1/]

2. For interior collectors in an array:

$GC_{PN} = \pm$ [GC_p for $30° < \theta \leq 45°$ and zone 2]

$GC_{PN} = \pm [GC_{PN} - 0.5]$ if $S > 0$[1/]

II. Collectors Mounted on Flat Roofs, $\theta \leq 10°$ - (see figure 2)

A. Basic net loads on individual collectors

1. For end collectors in an array or individual collector systems:

$GC_{PN} = \pm 1.5$[GC_p for zone 2]

2. For interior collectors in an array:

$GC_{PN} = \pm$ [GC_p for zone 2]

B. Collector mounted on flat roofs with parapets

No reduction is allowed in obtaining the net loads on an individual collector.

C. Collectors mounted in multiple rows on flat roofs (no lateral offset between rows in direction parallel to rows) - provided $D < 2.5\ \ell$, see figure 2

No reduction is allowed in obtaining the net loads on an individual collector.

III. Collectors Mounted in Ground Installations

1/ Note that GC_{PN} used for net loads is a negative number.

A. For collectors placed next to a building wall - berm units (see figure 3):

$GC_{PN} = \pm$ [GC_p for appropriate wall zone]

B. For single row of collectors mounted close to ground and not leaning against a building:

Use GC_{PN} equal to the sum of the magnitudes of the negative pressure coefficient and 70 percent of the positive pressure coefficient, each for the appropriate wall zone.

$GC_{PN} = \pm\{|\text{neg. } GC_p| + 0.7\ |\text{pos. } GC_p|\}$ for the appropriate wall zone

C. Multiple rows of collectors mounted close to the ground and not leaning against a building (no lateral offset between rows in direction parallel to rows) - provided $D < 2.5\ \ell$; see figure 4

Pressure coefficients on individual collectors are obtained using the guidelines in section 6.3 - III.B and may be reduced as follows:

1. For collectors on interior rows:

$$GC_{PN} = [GC_{PN} \text{ from sec. 6.3-III.B}][1.0-(\frac{90-\beta}{15})(0.15)]$$

but the value of GC_{PN} shall not be taken less than 40 percent of the unreduced value of GC_p.

2. For collectors in the last row:

$$GC_{PN} = [GC_{PN} \text{ from sec. 6.3-III.B}][1.0-(\frac{90-\beta}{15})(0.10)]$$

but the value of GC_{PN} shall not be taken less than 60 percent of the unreduced value of GC_p.

6.4 WIND LOADS ON SOLAR COLLECTOR SYSTEM SUPPORTS - SAFETY REQUIREMENTS

CRITERION: The support brackets and frames for holding the collector array shall withstand the wind loads based on the following analytical procedures and guidelines without exceeding the allowable stresses that are conventionally used for the material in question. The frame shall be designed in such a manner that it is capable of transmitting the prescribed wind loads to the ground or to the roof or walls of a building without experiencing distortion or displacements in excess of the strains corresponding to the allowable stresses for the material in question.

ANALYTICAL PROCEDURE: Design wind pressures for an array of collector panels to be used in determining net loads on the array should be determined in accordance with the appropriate following equation:

A. For collectors which are not an integral part of the roof, i.e. are placed on top of the roof or are actually separated from the roof surface

$$p_{NS} = q_{h_1} (GC_{PNS})$$

B. For collectors which are an integral part of the roof, i.e. the back surface is effected by the internal pressure of the building.

$$p_{NS} = q_{h_1} (GC_{PNS}) - q_{h_1} (GC_{Pi})$$

where: $GC_{Pi} = \pm\ 0.25$, whichever creates the worst loading case

GC_{PNS} is obtained from the ANSI A58.1-1980/Draft table "External Pressure Coefficients for Loads on Building Components and Cladding for Buildings with Height $h < 60$ ft", using the following guidelines.

NOTE: Obtain GCp from the negative values in the tables but recognize that the loads can act in either direction normal to the collector.

GUIDELINES FOR USING ANSI A58.1-1980/DRAFT TO OBTAIN NET PRESSURE COEFFICIENTS FOR A SOLAR COLLECTOR ARRAY (2 or more collectors)

I. Collectors Mounted on Sloped Roofs, $\theta > 10°$[1/] see figure 1)

A. For collectors parallel to the roof slope, $\beta = 0°$:

$GC_{PNS} = \pm$ [GC_p for zone where majority of collectors are located]

B. For collectors inclined to the roof slope, $\beta > 0°$:

$GC_{PNS} = \pm$ [GC_p for $30° < \theta \leq 45°$ and zone 2]

II. Collectors Mounted on Flat Roofs, $\theta \leq 10°$ - (see figure 2)

A. For basic net loads on an array of collectors:

1/ For roof slopes in excess of 45°, use values for 45°.

$GC_{PNS} = \pm$ [GCp for zone 2]

B. For array of collectors mounted on a flat roof with parapets:

No reduction is allowed in obtaining the net load on an array of collectors.

C. For multiple arrays of collectors (no lateral offset between rows in direction parallel to rows) - provided $D < 2.5d$ - (see figure 2):

For interior rows only:

$GC_{PNS} = \pm$ [GCp for zone 1]

III. Collectors Mounted in Ground Installations

A. For an array of collectors placed next to a building wall - berm units (see figure 3):

$GC_{PNS} = \pm$ [GCp for zone where majority of collectors are located]

B. For a single array of collectors mounted close to ground and not leaning against a building (see figure 4):

$GC_{PNS} = \pm$ [GCp for zone 5]

C. For multiple arrays of collectors mounted close to ground and not leaning against a building (no lateral offset betwee rows):

No reduction is allowed for interior rows.

6.5 SAFETY OF BUILDINGS AND FOUNDATIONS SUPPORTING COLLECTOR SYSTEMS

CRITERION: Buildings and foundation systems supporting elevated or ground mounted collector arrays shall resist the appropriate loads and moments transmitted by the collector array frame as defined in section 6.4 of this report. For roof or wall mounted collectors, a path must be provided for transmitting the wind loads to the structural frame.

7. EXAMPLES

In the following three subsections, examples are presented to illustrate the use of the design criteria and guidelines given in section 6. Wind loads will be computed for both end and interior collectors, although it is recognized that in most cases all collectors should be designed to withstand the larger loads experienced by the end collectors.

7.1 COLLECTORS MOUNTED ON A SLOPED ROOF

Consider the case of an array of eleven collectors mounted on the sloped roof of a one story building as shown in figure 1. The building is to be built in Omaha, Nebraska and is 32 feet[1/] wide by 50 feet long. The eave height is 10 ft and the ridge height will be 15.5 ft since the roof is symmetric and has a pitch of 20 degrees. The solar collector installation is characterized by the following parameters illustrated in figure 1: $\beta = 25°$, $\ell = 8$ ft, $w = 4$ ft, $B = 44$ ft, $c_1 = 4.5$ ft and $a = 3.2$ ft. Also, the bottom edge of the collector is to be raised 3 ft above the roof level, $S = 2.8$ ft, so that snow will slide off the collector. In this example it is assumed that each collector has a tributary area, A, of 32 sq ft and the entire array has a tributary area of 352 square ft. Because the collector is elevated to allow snow to slide off and is mounted at a slope which is considerably steeper than the roof slope, h_1 is equal to 17.4 ft which is greater than the roof ridge height and h_2 is equal to 4.7 ft. Consquently, A' is equal to 0.83. From figure 1 it can be seen that collectors C1.1 through C1.10 are in zone 1 and that collector C1.11 is in zone 2 (more than 30 percent of C1.11 is in zone 2).

Using this information, the wind loads are computed following the guidelines given in section 6. The procedure is as follows:

Calculate Velocity Pressure: from section 6.1.4

(1) Velocity Pressure Exposure Coefficient: K_z

$$K_z = K_{h_1} = K(17\ \text{ft}) = 0.83$$

(2) Importance Factor: I

I (collector) = 1.00 (category I)
I (cover plate) = 0.95 (category IV)

(3) Basic Wind Speed: V = 80 mph

(4) Velocity Pressure: q_z

$$q_z\ (\text{collector}) = q_{h_1}\ (\text{collector}) = 0.00256\ [0.83][(1.00)(80)]^2$$

$$q_{h_1}\ (\text{collector}) = 13.6\ \text{psf}$$

$$q_z\ (\text{cover plate}) = q_{h_1}\ (\text{cover plate}) = 0.00256\ [0.83][(0.95)(80)]^2$$

$$q_{h_1} = (\text{cover plate}) = 12.3\ \text{psf}$$

1/ For conformity with the American National Standard A58.1-1980/Draft, English units are used throughout Parts I, II, and III of this report. For conversion to SI units, see p. viii.

Wind Loads on Cover Plates: from section 6.2

$p = q_{h_1}(GC_p) - q_{h_1}(GC_{Pi})$

positive pressures: from section 6.2.I.B.1

$GC_p = 1.2$ and since $GC_{Pi} = \pm 0.25$

$p = (12.3)(1.2) - (12.3)(-0.25) = 17.8$ psf

suctions: from section 6.2.I.B.2

a) End Collectors: Note that A' > 0.5 since h_1 > ridge height

$GC_p = -2.5 - 0.5 = -3.0$

$p = (12.3)(-3.0) - (12.3)(0.25) = -40.0$ psf

b) Interior Collector:

$GC_p = -1.55$

$p = (12.3)(-1.55) - (12.3)(0.25) = -22.1$ psf

Wind Loads on Individual Collectors: from section 6.3

$p_N = q_{h_1}(GC_{PN})$

Note that pressure coefficients are obtained from the negative values in the tables and are assumed to act in either direction normal to the collector.

From section 6.3.I.B

(1) End Collector: Note that A' > 0.5 since h_1 > ridge height also S > 0.0

GC_{PN} = [GC_p for angle θ and zone 2] - 1.0

$GC_{PN} = -2.5 - 1.0 = -3.5$

$p_N = (13.6)(-3.5) = \pm 47.6$ psf

Wind load = (± 47.6)(32) = ± 1523 lbs

(2) Interior Collector: since S > 0.0

$GC_{PN} = -1.55 - 0.5 = -2.05$

$p_N = \pm(13.6)(-2.05) = \pm\ 27.9$ psf

Wind load = (±27.9) (32) = ± 893 lbs

Wind Loads on Solar Collector System Supports: from section 6.4

$p_{NS} = q_{h_1}(GC_{PNS})$

Note that pressure coefficients are obtained from the negative values in the tables and are assumed to act in either direction normal to the collector.

From section 6.4.I.B A = 352 sq ft

$GC_{PNS} = -1.4$

$p_{NS} = \pm\ (13.6)(-1.4) = \pm\ 19.0$ psf

Net wind load = (± 19.0)(352) = ± 6688 lbs

7.2 COLLECTORS MOUNTED ON A FLAT ROOF

Consider the case of three arrays of eleven collectors mounted on the flat roof of a one story building as shown in figure 2. The building is to be built in New Orleans, Louisiana and is 40 ft wide by 60 ft long. The eave height is 10 ft and there is a 2.5 foot high parapet, ($H = 2.5$ ft and $\phi = 90°$) around the edge of the building. The solar collector installation is characterized by the following parameters illustrated in figure 2: $\beta = 30°$, $\ell = 8$ ft, $w = 4$ ft, $B = 44$ ft, $D = 10$ ft and $a = 4$ ft. The bottom edge of the collector is raised 2.0 ft above the roof level ($S = 2.0$ ft) for service of the roof membrane [9]. Therefore, h_1 is equal to 14.0 feet. It is assumed that each collector has a tributary area of 32 square feet and that each array has a tributary area of 352 sq ft. From figure 2 it can be seen that all the collectors fall within zone 1 except for C1.11, C2.11 and C3.11 which fall within zone 2 (more than 30 percent of C1.11, C2.11 and C3.11 is in zone 2).

Using this information, the wind loads are computed following the guidelines given in section 6. The procedure is as follows:

Calculate Velocity Pressure: from section 6.1.4

(1) Velocity Pressure Exposure Coefficient : K_z

$K_z = K_{h_1} = K(14\text{ ft}) = 0.80$

(2) Importance Factor: I

I (collector) = 1.05 (category I)

I (cover plate) = 1.00 (category IV)

(3) Basic wind speed: $V = 100$ mph

(4) Velocity Pressure: q_z

q_z (collector) = q_{h_1} (collector) = $0.00256[0.80][(1.05)(100)]^2$

q_{h_1} (collector) = 22.6 psf

q_z (cover plate) = q_{h_1} (cover plate) = $0.00256[0.80][(1.00)(100)]^2$

q_{h_1} (cover plate) = 20.5 psf

<u>Wind Loads on Cover Plates</u>: from section 6.2

$p = q_{h_1}(GC_p) - q_{h_1}(GC_{Pi})$

<u>positive pressures</u>: from section 6.2.II.A.1

$GCp = -(-1.3) = 1.3$ and since $GC_{Pi} = \pm 0.25$

$p = (20.5)(1.3) - (20.5)(-0.25) = 31.8$ psf

<u>suctions</u>: from section 6.2.II.A.2

a. End Collectors: Note $S > 0$

$GCp = 1.2[-2.1] - 0.5 = -3.0$

$p = (20.5)(-3.0) - (20.5)(0.25) = -66.6$ psf

b. Interior Collectors:

$GCp = 1.1[-1.3] = -1.4$

$p = (20.5)(-1.4) - (20.5)(0.25) = -33.8$ psf

*Allowable reductions to suction on end collectors due to parapets: from section 6.2.II.B

$GC_p = [-3.0]\{1.0 - [3(H-S)/\ell \sin\beta]\}$

$GCp = [-3.0]\{1.0 - [3(2.5-2.0)/8 \sin 30°]\}$

$GCp = [-3.0][.63] = -1.9$

$p = (20.5)(-1.9) - (20.5)(0.25) = -44.1$ psf

*Allowable reductions to suction for end collectors on interior rows of multiple row installation: from section 6.2.II.C.1

$GC_p = [-3.0][1.0 - (\frac{90-30}{15})(0.15)]$

$GC_p = -1.2$

However, GC_p for zone 1 = -1.3

$\therefore$ $GC_p = -1.3$

$p = (20.5)(-1.3) - (20.5)(0.25) = -31.8$ psf

*Allowable reductions to suctions on end collectors on last row of multiple row installation: from section 6.2.II.C.2

$GC_p = [-3.0][1.0 - (\frac{90-30}{15})(0.10)]$

$GC_p = -1.8$

$p = (20.5)(-1.8) - (20.5)(0.25) = -42.0$ psf

Based on these calculations a reasonable approach would be to design the cover plates for the end collectors to withstand 44 psf and the cover plates for the interior collectors to withstand 34 psf. A more practical approach might be to design all the cover plates for 44 psf.

Wind Loads on Individual Collectors: from section 6.3

$p_N = q_{h_1}(GC_{PN})$

From section 6.3.II.A

(1) End Collector:

$GC_{PN} = \pm 1.5[-2.1] = \pm 3.2$

$p_N = (22.6 \text{ psf})(\pm 3.2) = \pm 72.3$ psf

Wind load = $(\pm 72.3)(32) = 2314$ lbs

(2) Interior Collectors:

$GC_{PN} = \pm [-2.1] = \pm 2.1$

$p_N = (22.6 \text{ psf})(\pm 2.1) = \pm 47.5$ psf

Wind load = $(\pm 7.5)(32) = 1520$ lbs

Wind Loads on Solar Collector System Supports: from section 6.4

$p_{NS} = q_{h_1} (GC_{PNS})$

From section 6.4.II.A $A = 352$ sq ft

$GC_{PNS} = \pm 1.5$

$p_{NS} = (22.6 \text{ psf}) (\pm 1.5) = \pm 33.9$ psf

Net wind load = $(\pm 33.9)(352) = 11{,}933$ lbs

*Allowable reduction for interior rows

$GC_{PNS} = \pm 1.2$

$p_{NS} = (22.6 \text{ psf}) (\pm 1.2) = \pm 27.1$ psf

Net wind load on interior array =

$(\pm 27.1)(352) = 9539$ lbs

7.3 DESIGN OF COLLECTOR COVER PLATES FOR A VARIETY OF INSTALLATIONS

Consider the case of a glass manufacturer who is producing solar collector cover plates which he has certified to withstand 55 psf wind loads. It is possible to use the criteria and guidelines contained in section 6 to define categories of installations for which these cover plates would be suitable.

The largest pressure coefficients for cover plates assumed to have an area of 32 sq ft in any of the installations covered by the provisions is -3.25. This is true for collectors mounted on sloped or flat roofs or on ground installations. Noting that $p = \pm 55 \text{ psf} = q_{h_1} GC_p = q_{h_1} (-3.25)$,

$$q_{h_1} = 16.9 \text{ psf}$$

Also for areas which are not subject to hurricane winds,

$$q_{h_1} = 16.9 \text{ psf} = 0.00256\, K_z\,]0.95\, V]^2$$

or $K_z V^2 = 7315$

$K_z = 1.13$ at $z = 50$ ft

$K_z = 0.87$ at $z = 20$ ft

for $K_z = 1.13$, $V = 80.5$ mph

for $K_z = 0.87$, $V = 91.7$ mph

Consequently, these cover plates would meet the design criteria outlined in this report for any collector installation located within map regions having a basic wind speed less than 80 mph and mounted at elevations less than 50 ft or located within map regions having a basic wind speed less than 90 mph and mounted at elevations less than 20 ft.

Similar general provisions could be derived for individual collectors, mounting brackets or entire arrays. Further provisions could be made restricting use of the collectors in configurations which carry a wind load penalty such as those which extend well above the roof ridge.

8. REFERENCES

1. Tieleman, H. W., Akins, R. E., and Sparks, P. R., "An Investigation of Wind Loads on Solar Collectors, With Appendices I and II," Virginia Polytechnic Institute and State University, VPI-E-80-1, Blacksburg, Virginia, January 1980. (Available from NTIS, NTIS access numbers BP80158744, PB80158751, and PB80158769 respectively).

2. Building Code Requirements for Minimum Design Loads in Buildings and Other Structures, American National Standard A58.1-1980/Draft, American National Standards Institute, New York, 1980.

3. Simiu, E., Changery, M. J., and Filliben, J. J., "Extreme Wind Speeds at 129 Stations in the Contiguous United States," National Bureau of Standards, Building Science Series 118, Washington, D.C., March 1979.

4. Batts, M. E., Cordes, M. R., Russell, L. R., Shaver, J. R. and Simiu, E., "Hurricane Wind Speeds in the United States," National Bureau of Standards, Building Science Series 124, Washington, D.C., May 1980.

5. Tieleman, H. W. and Reinhold, T. A., "Wind Tunnel Model Investigations for Basic Dwelling Geometries," Virginia Polytechnic Institute and State University, VPI-E-76-8, Blacksburg, Virginia, May 1976.

6. Davenport, A. G., Surry, D. and Stathopoulos, T., "Wind Loads on Low-Rise Buildings, Final Report of Phases I and II," University of Western Ontario, BLWT-SS8-1977, London, Ontario, Canada, August 1977.

7. Marshall, R. D., "A Study of Wind Pressures on a Single-Family Dwelling in Model and Full Scale," Journal of Industrial Aerodynamics, 1 (1975), pp. 177-199.

8. Tieleman, H. W., Akins, R. E. and Sparks, P. R., "A Comparison of Wind-Tunnel and Full-Scale Wind Pressure Measurements on Low-Rise Structures," Proceedings of the 4th Colloquium on Industrial Aerodynamics, Aachen, Germany, June 19-20, 1980.

9. Mathey, R. G. and Rossiter, W. J., "Guidelines for Installation of Solar Components on Low-Sloped Roofs," National Bureau of Standards, Technical Note 1134, Washington, D.C., September 1980.

TABLE 1.a

Peak Negative Pressure Coefficients* for Top Surface of Collectors (Cover Plates). Comparison of Price's Fork Model and Full-Scale Data, $S/\ell = .062$

Model Test Data			Full-Scale Test Data	
Wind Direction	Coefficients from Predicted Peaks, Data Filtered at 50 Hz	Coefficients from Predicted Peaks, Corrected 10 Hz Filtered Data	Wind Direction	Coefficients from Measured Peaks
360	- .8**	- .7**	1	- .9
0	- .9**	- .9**	4	- .7
30	- .7	- .7		
60	- .6	- .6	74	-1.0
90	- .6	- .6	74	-1.2
			172	-4.1
180	-1.3	-1.4	173	-2.9
200		-2.2	204	-4.5
210	-1.7	-2.7	212	-4.1
220		-2.6	214	-3.8
230		-2.4		
240	-2.3	-2.6	246	-4.3
250		-2.8	247	-3.5
			253	-3.8
260		-2.6	259	-4.6
			263	-5.1
			264	-4.0
270	-2.2	-2.5	269	-4.5
			274	-4.4
			282	-4.2
			283	-4.4
300	-1.2	-1.9		

* Coefficients are based on mean hourly wind speeds. (Divide by ~ 1.61 to convert to coefficient for use with fastest mile wind speed)

** Positive mean pressure coefficient.

TABLE 1.b

Peak Positive Pressure Coefficients* for Top Surface of Collectors (Cover Plates). Comparison of Price's Fork Model and Full-Scale Data, S/ℓ = .062

Model Test Data			Full-Scale Test Data	
Wind Direction	Coefficients from Predicted Peaks, Data Filtered at 50 Hz	Coefficients from Predicted Peaks, Corrected 10 Hz Filtered Data	Wind Direction	Coefficients from Measured Peaks
360	0.9	0.9	1	1.1
0	1.0	1.0	4	1.0
30	0.5**	0.5**		
60	0.2**	0.2**	74	0.2
90	0.2**	0.3**	74	0.0
			172	0.1
180	0.2**	0.4**	173	0.1
200		0.5**	204	0.2
210	0.0**	0.7**	212	-0.1
220		0.6**	214	0.0
230		0.4**		
240	0.1**	0.6**	246	0.5
250		0.6**	247	0.1
			253	0.2
260		0.5**	259	0.2
			263	0.0
			264	-0.1
270	0.6**	0.6**	269	-0.1
			274	0.7
			282	1.0
			283	0.7
300	0.8**	1.4**		

* See note on table 1.a.

** Negative mean pressure coefficient.

TABLE 2.a

Peak Negative Pressure Coefficients* for Net Loads on Collectors.
Comparison of Price's Fork Model and Full-Scale Data, S/ℓ = .062

Model Test Data			Full-Scale Test Data	
Wind Direction	Coefficients from Measured Peaks, Data Filtered at 50 Hz	Coefficients from Predicted Peaks, Corrected 10 Hz Filtered Data	Wind Direction	Coefficients from Measured Peaks
360	.1	- .5	1	- .2
0	0.0	-1.0	4	- .5
30	- .1	- .5		
60	- .1	- .6	74	- .3
90	- .2	- .7	74	- .6
			172	-1.3
180	- .3	-1.4	173	- .9
200		-2.0	204	-1.1
210	- .4	-2.4	212	-1.9
220		-2.3	214	-1.6
230		-2.1		
240	- .5	-2.7	246	-1.1
250		-2.5	247	-1.1
			253	-1.7
260		-2.5	259	-2.1
			263	-2.1
			264	-1.5
270	- .5	-2.5	269	-1.6
			274	-2.1
			282	-1.6
			283	-1.7
300	- .1	-1.6		

* Coefficients are based on mean hourly wind speeds. (Divide by ~ 1.61 to convert to coefficient for use with fastest mile wind speed)

TABLE 2.b

Peak Positive Pressure Coefficients* for Net Loads on Collectors. Comparison of Price's Fork Model and Full-Scale Data, $S/\ell = .062$

Model Test Data			Full-Scale Test Data	
Wind Direction	Coefficients from Measured Peaks, Data Filtered at 50 Hz	Coefficiencs from Predicted Peaks, Corrected 10 Hz Filtered Data	Wind Direction	Coefficients from Measured Peaks
360		1.9	1	2.5
0	1.9	2.3	4	1.9
30	1.6	1.2		
60	1.1	0.9	74	0.9
90	0.6	0.8	74	1.1
			172	0.7
180	0.3	1.3	173	0.5
200		1.6	204	1.5
210	0.5	1.7	212	1.4
220		1.6	214	1.1
230		1.5		
240	0.5	2.4	246	2.8
250		2.0	247	1.5
			253	
260		2.0	259	2.4
			263	2.0
			264	1.8
270	0.7	2.2	269	1.8
			274	1.9
			282	2.1
			283	2.0
300	1.4	2.3		

* See note on table 2.a.

Table 3

Peak Pressure Coefficients* for Top Surface of Collectors (Cover Plates) Mounted Flat on a Building Roof

Roof Pitch	No. of Stories	Positive or Negative Peak Pressure	End Collector in Array			Middle Collector in Array		
			Zone**	Test Results	ANSI A58.1-1980/Draft	Zone**	Test Results	ANSI A58.1-1980/Draft
30°	1	Negative	1	-1.2	-1.2	1	-1.2	-1.2
	1	Positive	1	0.6	-	1	.9	-
	2	Negative	1	-1.2	-1.2	1	-1.1	-1.2
	2	Positive	1	0.4	-	1	0.4	-
45°	1	Negative	1	-1.2	-1.3	1	-1.1	-1.3
	1	Positive	1	0.9	1.2	1	1.2	1.2
	2	Negative	1	-1.1	-1.3	1	-0.8	-1.3
	2	Positive	1	0.6	1.2	1	0.7	1.2
60°	1	Negative	1	-1.0	-1.3	1	-0.9	-1.3
	1	Positive	1	1.1	1.2	1	1.0	1.2
	2	Negative	1	-1.1	-1.3	1	-0.8	-1.3
	2	Positive	1	0.9	1.2	1	0.8	1.2
30° Price's Fork Model	1	Negative	2	-1.8	-2.5	1	-1.3	-1.2
	1	Positive	2	0.7	-	1	0.6	-
30° Price's Fork Full-Scale	1	Negative	2	-2.8	-2.5	1		
	1	Positive	2	0.7	-	1		

* Coefficient for use with fastest mile wind speeds.

** Roof zone after ANSI A58.1-1980/Draft; if a collector is located in more than one zone, it is assumed to be located in the highest zone where more than 30 percent of its projected area is located.

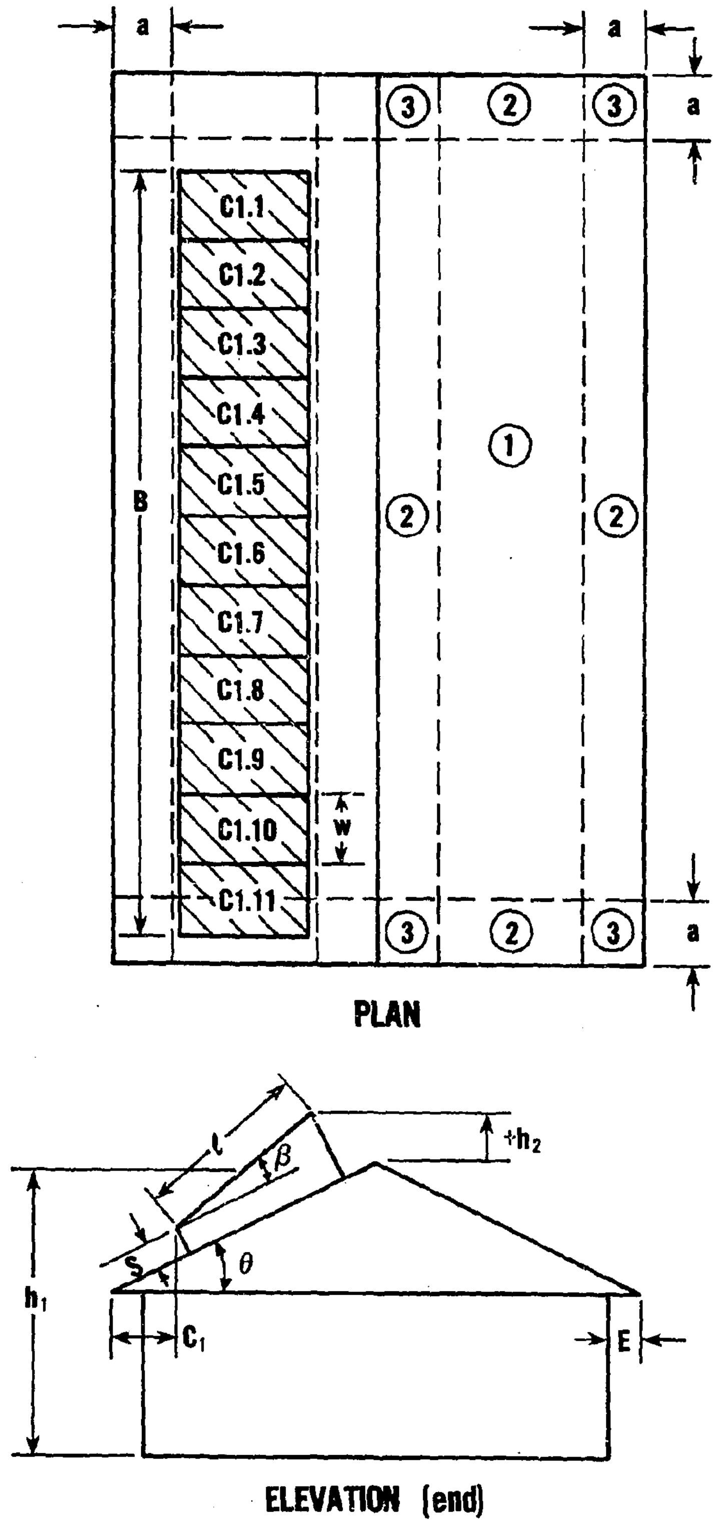

Figure 1. Solar Collector Systems Mounted on a Sloped Roof.

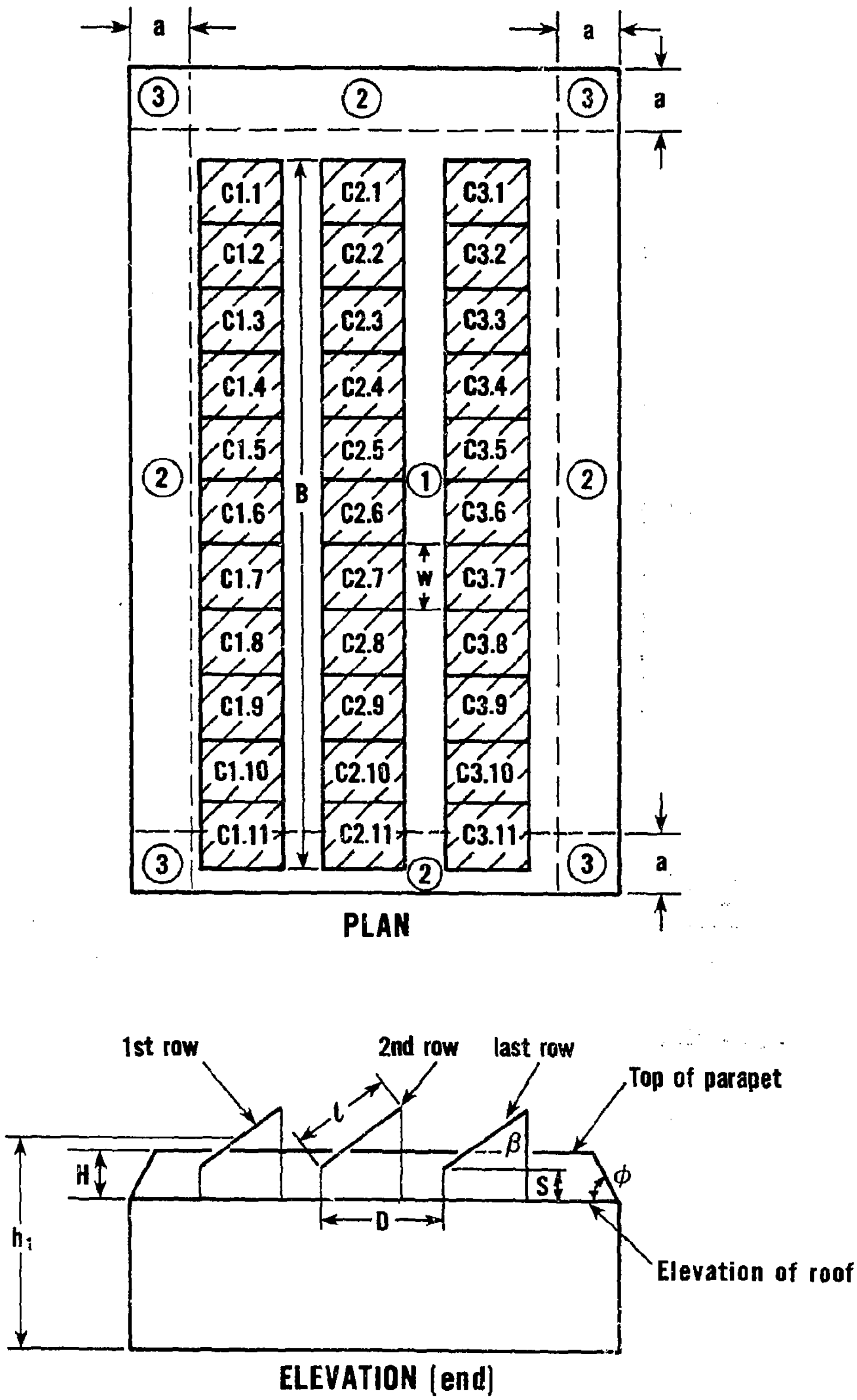

Figure 2. Solar Collector System Mounted on a Flat Roof.

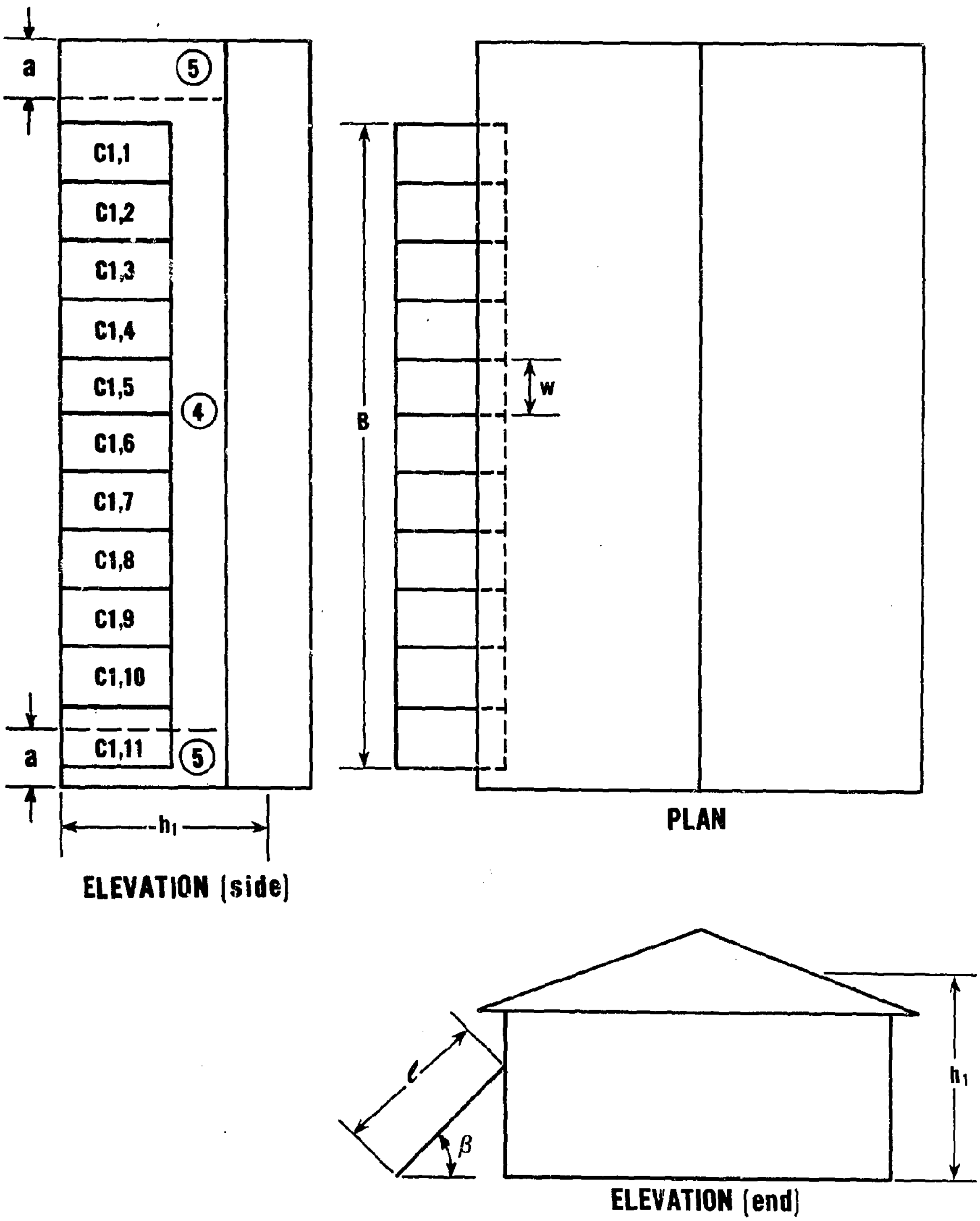

Figure 3. Collector Systems in Ground Installations Next to a Building - Berm Units.

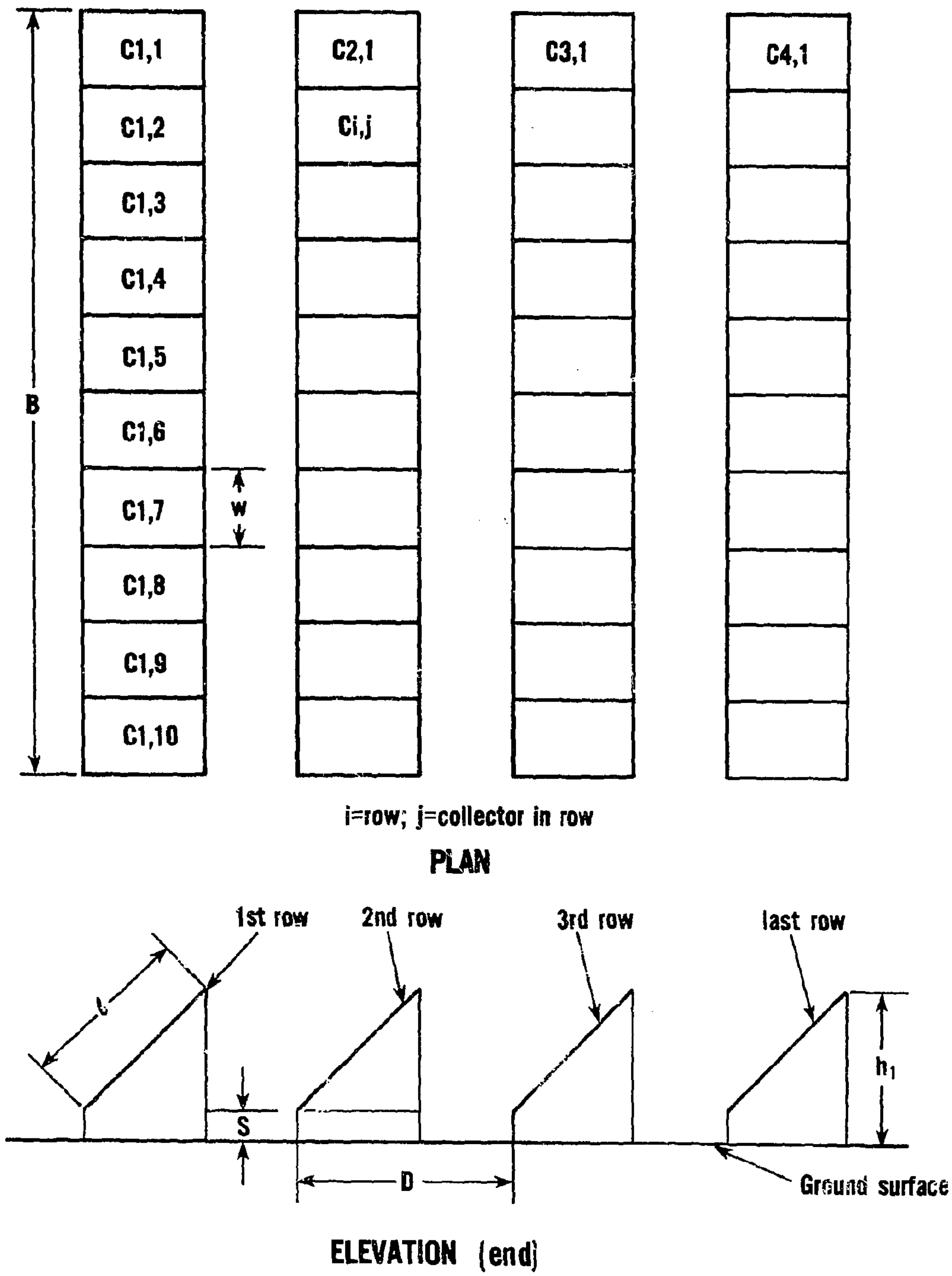

Figure 4. Collector Systems in Ground Installation in Open Location.

PART II

EARTHQUAKE LOADS ON SOLAR COLLECTORS

by

Charles W.C. Yancey

LIST OF TABLES

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NOTATION

A_p: Force multiplier which accounts for amplification of motion experienced by the supporting structure.

C_p: Horizontal force factor to be used in obtaining the ANSI equivalent static lateral force.

T_a: Natural period of solar collector panels and their support system, seconds.

1. INTRODUCTION

This section presents information applicable to the design and evaluation of new or replacement solar collectors and their supports when they are to be subjected to seismic loads. This information is based upon current seismic design practice for mechanical and electrical elements as incorporated in building codes and standards. Where necessary, the code and standard provisions are adapted to reflect the specific characteristics of solar collector systems.

2. RELATIVE IMPORTANCE OF SEISMIC FORCES IN THE DESIGN OF SOLAR COLLECTOR SYSTEMS

In the event of an earthquake the components of solar collector systems would be subjected to inertial forces that are directly proportional to their mass. Since the self weight of solar collectors is relatively small, it is inferred that the seismic forces applicable to these elements are also relatively small. For example, in the case of flat plate collectors, the unit weight is of the order of 10 psf1/. Using the equivalent static force approach specified in the 1980 draft revision of American National Standard A58.1 [1]* each square foot of flat plate collector panel would experience a lateral seismic force of about 5 lb. Upon comparing this order of magnitude with current code and standard design loads for wind and snow, it is concluded that seismic forces would seldom govern the design of solar collector components and supports, even in the most highly seismic zones of the United States.

3. DESIGN OF SOLAR COLLECTORS SUBJECTED TO SEISMIC LOADS

In general, assemblies consist of standard-sized collector panels which are positively attached to triangular-shaped or diagonally-braced supports, that are in turn anchored directly to roof supports, a supporting slab, or footings. These assemblies would be categorized as "rigid" and "rigid-supported." All of the components of rigid and rigidly-supported solar collector systems, their supports and their connections to buildings or ground-supported members shall resist seismic forces as specified for parts and portions of structures in the 1980 draft revision of the ANSI A58.1 Standard [1]. The values of the factor C_p to be used in obtaining the ANSI Equivalent Static Lateral Force, consistent with ref. 1, are listed in table 1. The importance factor, I, shall be that which applies to the building being supplied by the solar collector system. The system shall resist the derived seismic forces without incurring failure or excessive deflection of the supporting and connecting elements.

1/ For conformity with the American National Standard A58.1-1980/Draft, English units are used throughout Parts I, II, and III of this report. For conversion to SI units, see p. viii.

* Numbers in brackets indicate references at the end of each part.

If in the judgement of the engineer, the solar collector system does not warrant being classified as rigid or rigidly-supported, the appropriate values of C_p shall be determined with consideration given to the dynamic properties of both the solar components and the building or structure on which they are placed. In any case, the values of C_p shall not be less than those listed in table 1. The natural period of the collector panels and their support system determines whether the assembly is to be considered rigid or flexible. (As a guide, an assembly should be considered flexible if its natural period $T_a > 0.05$ seconds).

In lieu of a rigorous dynamic analysis, flexible or flexibly-mounted collectors may also be analyzed by the Equivalent Static Force method. However, the force obtained by using the ANSI formula should be modified by the multiplier A_p, which accounts for the amplification of the motion experienced by the supporting structure. Published values for A_p have a range of $1.0 \leq A_p \leq 5.0$ [2].

4. REFERENCES AND BIBLIOGRAPHY

1. Building Code Requirements for Minimum Design Loads in Buildings and Other Structures, American National Standard A58.1-1980/Draft, American National Standards Institute, New York, 1980.

2. Seismic Design for Buildings, TM 5-809-10, NAVFAC P-355, AFM 88-3, Chap. 13, Departments of the Army, the Navy and the Air Force, Draft: January 1979.

3. Uniform Building Code, 1979 Edition, International Conference of Building Officials, Whittier, California, 1979.

4. Intermediate Minimum Property Standards Supplement for Solar Heating and Domestic Hot Water Systems, 4930.2, 1977 Edition, U.S. Department of Housing and Urban Development, Washington, D.C. 1977.

5. Yancey, C. W. C., and Camacho, A. A., "Aseismic Design of Building Service Systems: The State-of-the-Art," NBS Technical Note 970, National Bureau of Standards, Washington, D.C., September 1978.

6. Tentative Provisions for the Development of Seismic Regulations for Buildings, Applied Technology Council (ATC), ATC Publication ATC 3-06, National Bureau of Standards Special Publication 510, National Science Foundation Publication 78-8, U.S. Government Printing Office, Washington, D.C., 1978.

TABLE 1. Horizontal Force Factor "C_p" for Solar Collector Systems

Part of System	Direction of Horizontal Force	Value of C_p
Roof-supported flat plate and concentrating solar collectors	any direction	0.30
Ground-supported flat plate and concentrating solar collectors	any direction	0.20
Anchorages and supports for solar collectors and storage tanks	any direction	0.30
Storage tanks connected to or housed within the building	any direction	0.30
Transfer liquid pipes and storage tanks resting on the ground	any direction	0.20

PART III

SNOW DESIGN CRITERIA FOR FLAT-PLATE SOLAR COLLECTOR INSTALLATIONS

by

James Robert Harris

LIST OF FIGURES

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NOTATION

C_e: coefficient for exposure to wind
C_s: coefficient for slope
C_t: coefficient for thermal properties
H : actual clear height of collector above roof
H_c: nominal clear height for avoidance of drifting
h_b: height of balanced snow load
h_c: clear height from top of balanced load to top of obstruction
h_d: depth of drift
I : coefficient for level of risk
ℓ : length of obstruction
p_d: drift surcharge load
p_f: flat roof snow load
p_g: ground snow load
p_s: sloped roof snow load
W : width of drift
γ : density of snow

1. INTRODUCTION

Flat plate solar collectors are becoming an increasingly common building component, both for new and existing structures. Most solar collectors are located on building roofs, and there is a need for more specific design criteria to provide safety in the event of large snowfall. This report summarizes the findings of studies of snow accumulation around solar collectors conducted during the winter of 1978-79 and proposes specific design criteria. The structural loading criteria are based on the use of the 1980 draft revision of American National Standard A58.1, "Building Code Requirements for Minimum Design Loads in Buildings and Other Structures" [1]*. The criteria address the functioning and serviceability of solar collectors and buildings as well as safety against structural failure.

2. PERFORMANCE REQUIREMENTS

There are four basic requirements for solar collector installations with regard to their performance in case of snow:

***SAFETY OF COLLECTOR SYSTEMS: The collector systems should not collapse due to the weight of snow.

***SAFETY OF BUILDINGS SUPPORTING COLLECTOR SYSTEMS: The building should not collapse due to the weight of snow and of the collector systems.

***SERVICEABILITY OF COLLECTOR SYSTEMS: The collector systems should not suffer prolonged loss of operation due to snow cover.

***SERVICEABILITY OF BUILDINGS SUPPORTING COLLECTOR SYSTEMS: The building should not be adversely affected by the moisture and ice associated with snow accumulation around solar collectors.

It is pertinent to note that a collector system will alter the position and amount of snow retained on a roof. In view of this fact and of the second requirement, caution is needed in retrofitting collector systems on existing buildings.

3. FINDINGS OF STUDIES CONDUCTED IN 1979

Two studies were conducted for the National Bureau of Standards during the winter of 1978-79, one in the vicinty of Albany, New York, [2] and one in the Chicago area [3]. Twenty-six sites were studied, including a wide variety of configurations of flat plate collector systems. In addition, four sites in the Washington, D.C., area were observed by NBS personnel, and summaries of those observations are also included in this report.

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* Numbers in brackets indicate references at the end of each part.

There are two items of interest in the study of snow on and around solar collector systems: the amount (both volume and weight) of snow on the collector itself, as related to the amount of snow on the ground, and the difference in the amount of snow on the building from what would exist if no solar collectors were present. The basic physics of the problem includes the mechanics of falling and drifting snow around solar collectors and the melting and sliding of snow from solar collector surfaces. The studies addressed these issues in a qualitative manner, although some quantitative analysis was carried out on the data collected around Albany.

In most cases where observations were made during or shortly after snowfall, some snow was retained on the collector surfaces. This accumulation was generally small in comparison to the amount retained on other portions of the roof. Figures 1 and 2 illustrate light snow cover on the collectors following a snowfall of approximately six inches. It is apparent that such snow cover would prevent the operation of a solar collector, and that it would impose some load on the collector unit itself. Intuitively, it could be expected that the snow would quickly melt and slide off the collector surface. If this were consistently true, the short loss of operation would not be serious, and the maximum weight on the collector would be that of a single storm. Observations both confirm and deny this intuition, depending on other cirumstances. Figure 3, taken within a few minutes of figure 2, shows the anticipated melting and sliding, even on an over-cast day. The circumstances preventing the melting and sliding are of immediate interest.

Observations made in the Washington, D.C, area by the National Bureau of Standards, as well as observations recorded in ref. 3 serve to define necessary conditions for dependable shedding of snow from collector surfaces. Of first importance is the slope of the surface; only those collectors at a steep angle, more than about 50° with the horizontal, could be counted on to shed snow. Of nearly equal importance is the presence of obstructions in the path of the sliding snow; only those collectors completely free of obstructions were completely uncovered by sliding. Figures 4 and 5 both show collectors that are flush with the roof and have no gutters below, only the slopes are different. Most of the snow has slid off the steep collectors in figure 4, although about four inches of snow had fallen in the 24 hours before the photograph was taken. Considerable snow covers the collectors in figure 5, even though only one and one-half inches had fallen in the 24 hours before the photograph was taken. The two photographs were taken only one day apart in similar locations in the Chicago area.

For collectors that are mounted flush with the roof surface, the most dependable way of assuring slide-off is to extend the collectors to the bottom edge of the roof. A flattening of the roof slope beneath the collector, a change in the sliding resistance of the surface down the slope from the collector, or even a gutter may prevent the sliding action. Figure 6 illustrates the effect of a flatter slope below the collectors: those upper collectors above the lower roof are partially covered while the remaining upper collectors are clear. Figure 7 shows the influence of a gutter below the collector in forming an ice dam and preventing sliding.

Interviews with owners in the Chicago area revealed that collectors with unfavorable situations for clearance by sliding were out of operation for extended periods, up to two months in some cases, unless the snow was manually removed.

One further observation regarding the sliding of snow from solar collectors is that any structures beneath the solar collectors that might catch the sliding snow must be strong enough to carry the increased load. Measurements of snow accumulation on flat roofs beneath protruding collectors in the Albany area indicated that well over twice as much load existed there as at other locations on the same roof.

Collectors that protrude from the surface of the roof alter the air currents that carry both falling and blowing snow. The effect is much like that of a snow fence. Several interesting observations were made concerning this effect. The presence of a row of protruding collectors oriented normal to the wind tends to reduce the effect of the wind in removing snow from the roof. Depending on the amount of clearance below the protruding collectors, they can also serve to initiate drifts. The presence of several parallel rows of protruding collectors creates a situation comparable to a "sawtooth" or "northlight" roof, in which the valleys tend to fill in with snow. Figure 8 shows a building with many such rows of collectors. Figures 9 and 10 show the drifting effect on this same building, with snow depths well over four feet (1.2 m) following in eighteen inch (450 mm) snow accompanied by a significant wind.

Protruding collectors mounted with a significant clear space between the roof surface and the bottom edge of the collector were observed to have less of an effect on the formation of drifts. Also, because this clear space presented no obstructions to sliding, such collectors were less likely to remain covered by snow.

One last observation is that the presence of solar collectors seems to promote the growth of icicles and ice dams. Once a portion of a solar collector becomes clear on a sunny day, meltwater is produced even when the ambient temperatures are well below freezing. This water then freezes upon crossing cold surfaces or dripping into the air. An example is shown in figure 7. It is not unusual for roof leaks to be caused by such accumulation of ice and water, even without solar collectors, however some reports in the Chicago area indicated a possible correlation with the presence of solar collectors. The potential for damage to gutter systems is obvious.

4. DEVELOPMENT OF DESIGN CRITERIA

Although little quantitative work has been done specifically for snow distribution on and around solar collectors, it is possible to develop more specific design criteria from the findings of the referenced studies by relying heavily on the draft revision of ANSI A58.1 [1]. A very brief summary of the ANSI A58.1-1980/Draft provisions is appropriate in order to fully appreciate the criteria for solar collector installations.

4.1 THE SNOW LOAD CRITERIA OF ANSI A58.1-1980/DRAFT

The basic parameter for determination of design loads for snow is the weight of snow expected to accumulate on open ground at the building site. ANSI A58.1-1980/Draft contains maps that give the value for this parameter for much of the United States. (Note that the new edition of A58.1 does contain a somewhat different map than ANSI A58.1-1980/Draft). Areas where rough terrain or bodies of water create extreme local variation in snow accumulation are not included on the map, but procedures are described for establishing the ground snow load from reference publications. The basic roof design load is taken as 70 percent of the ground snow load, and further refinements are made by multiplying by three multiplicative coefficients, as follows:

i) C_e for exposure, varying form 0.8 for roofs exposed on all sides in windy areas to 1.2 for densely forested areas.

ii) C_t for thermal effects, varying from 1.0 for continuously heated structures with poor insulation to 1.2 for unheated structures.

iii) I for risk, varying from 0.8 for unimportant and uninhabited structures to 1.2 for essential structures.

Each of the coefficients has a value of 1.0 for average conditions.

The basic design load is further modified for sloped roofs depending on the slope, the slipperyness of the surface, and the thermal properties of the building. For roofs and portions of roofs sloped more than 70° with the horizontal, the design load is reduced to zero. Figure 11 summarizes the basic snow loads.

The effect of wind is incorporated into ANSI A58.1-1980/Draft in several ways. The unbalanced condition caused by removing half the snow load from any area is included for all roof types. Further unbalanced loading conditions are defined for hip, gable, arched, multiple folded plate, sawtooth, and barrel vault roofs. Drift surcharges are defined for the lower level of multilevel roofs and for roofs with vertical obstructions, such as mechnical equipment screens. Figures 12 and 13 show the unbalanced loads and the drift surcharges.

Another surcharge added to the basic load is the snow that might slide from high sloped roofs onto lower structures. Finally, a five to eight pounds per square foot surcharge for intense rain is recommended for certain climatic zones.

4.2 DEVELOPMENT OF CRITERIA SPECIFICALLY FOR SOLAR COLLECTOR INSTALLATIONS

The next section of this report contains specific criteria for design considering snow loads. The criteria for the design of collector systems are a relatively straightforward application of ANSI A58.1-1980/Draft [1]. The criteria for the design of roof structures of supporting buildings are more complex and more tentative, because the snow retention phenomenon is more complex and is not as well understood. The criteria have been developed to meet the basic performance requirements, once again making heavy use of ANSI A58.1-1980/Draft. Further study of the problem is warranted, both because the studies forming the basis of these criteria were so limited and because increasing use of solar flat plate collectors on roofs of buildings is forecast for the future.

5. DESIGN CRITERIA

5.1 CRITERION FOR THE SAFETY OF FLAT PLATE SOLAR COLLECTORS

CRITERION: Flat plate solar collector systems shall support the basic uniform snow load specified in ANSI A58.1-1980/Draft without exceeding the allowable stresses that are conventionally used for the materials in question.

COMMENTARY: With respect to the application of the ANSI A58.1-1980/Draft provisions in this situation, several items deserve comment. First, in those regions where the design snow load represents a winter-long accumulation of many snowfalls rather than a single large storm, the criterion is likely to be conservative because of the tendency for snow to disappear from collectors more rapidly than from the adjoining roof. But because snow has been observed to remain on collectors for months at a time during a severe winter, it does not appear appropriate to base the design of the collectors on statistics for a single large snowfall. Should the design of collectors prove to be expensive because of this criterion, which seems unlikely in view of the wind loads that such systems must withstand, further study of the problem would be warranted.

Second, the coefficient for thermal effect, C_t, should be taken as 1.3, the maximum value, for collectors that protrude from the roof, because they will generally be cold until the snow is at least partially removed. The thermal coefficient for flush collectors would depend on the insulation and thermal characteristics of the inoperative collector, the structure, and the space below.

Third, the modification for slope given in ANSI A58.1-1980/Draft should be applied using the "unobstructed slippery surface" curve only if the path of sliding snow is truly unobstructed. Collectors placed in locations likely to be involved in large drifts or to receive snow sliding from sloped surfaces above should be designed to resist the appropriate surcharges, as defined in ANSI A58.1-1980/Draft and the following criteria for supporting structures.

5.2 CRITERIA FOR THE SAFETY OF BUILDINGS SUPPORTING COLLECTOR SYSTEMS

Four criteria are necessary to satisfy adequately the second basic requirement, one for collectors mounted flush with the roof, two for collectors protruding from the roof and one for surfaces that may receive snow sliding off collectors:

5.2.1 Buildings Supporting Flush Collectors

CRITERION: A building supporting collectors mounted flush with the roof shall resist the appropriate uniform and unbalanced loads specified in ANSI A58.1-1980/Draft as any other roof with a slippery surface.

COMMENTARY: Collectors that are flush with the roof surface do not appreciably affect the total snow retention and distribution when compared to any other slippery surfaced roof of the same configuration.

5.2.2 Buildings Supporting Protruding Collectors

H is the clear height between the roof surface and the lowest obstruction presented by the solar collector system (see figure 14).

a) CRITERION: A building supporting protruding collectors that have a clear height H of more than H_c (defined subsequently) shall resist the appropriate uniform and unbalanced loads from ANSI A58.1-1980/Draft plus the sliding surcharge defined subsequently without considering drifting due to the collectors.

For determination of the loads from ANSI A58.1-1980/Draft, the coefficient for exposure, C_e, shall be modified as follows: for building and sites that would indicate C_e values of 0.8 to 1.0, take C_e as 1.1, and for buildings and sites that would indicate C_e values over 1.0, take C_e as 1.2.

a.1) DEFINITION: H_c is three feet [1/] unless the ground snow load is over 60 pounds per square foot, in which case it is:

$$H_c = p_g \cdot C_t \cdot I / 25$$

1/ For conformity with the American National Standard A58.1-1980/Draft, English units are used throughout Parts I, II, and III of this report. For conversion to SI units, see p. viii.

where C_t and I are the coeffieicnts for thermal and risk characteristics in ANSI A58.1-1980/Draft and p_g is the ground snow load in pounds per square foot.

a.2) DEFINITION: The sliding surcharge shall be taken as a uniform load applied as a strip at the foot of the collector row with a width equal to one-half the horizontal projection of the collector row. The total load shall be equal to the design load for the sloped collector, modified for the slope factor (see the criterion in section 5.1 and see figure 15).

b) CRITERION: A building supporting protruding collectors that do not have a clear height H of more than H_c shall resist the appropriate uniform and unbalanced loads from ANSI A58.1-1980/Draft with the modifications to C_e specified in section 5.2.2a plus the following loads to account for drifting and sliding of snow: 1) a single row of collectors shall be treated as a vertical obstruction with the drift surcharge as specified in ANSI A58.1-1980/Draft; 2) parallel rows of collectors shall be treated as a modified sawtooth roof by considering the toe of the collector as the valley of the equivalent sawtooth and the top of the collector as the ridge of the sawtooth (see figure 16).

COMMENTARY: Protruding collectors alter the air currents that carry falling and blowing snow, much like a snow fence. The increase in C_e coefficients over those specified by ANSI A58.1-1980/Draft is intended to account for this. The increase in C_e is attractive intuitively and seems justified based on the limited data from the studies [2, 3].

Protruding collectors tend to be more free of snow as the clear space between them and the roof increases, particularly if they are high enough to avoid any involvement with drifts on the roof. The definition for minimum clear space H_c is tentative, due to the limited studies made so far, and it should be the subject of further study. One pertinent source of information is the design of "blower type" snow fences (snow fences designed to use the wind to keep an area clear of snow by funneling wind across a surface at a higher velocity). Such designs are based on a minimum clear space of four feet [4]. Also, it appears reasonable that the minimum clear height depends on the anticipated height of snowpack for the maximum ground load at the location.

Protruding collectors that do not have a high enough clear space tend to become involved in drifts. Not enough data exists to confirm for solar collectors the distribution or the magnitudes of drift loads specified in ANSI A58.1-1980/Draft, but the loads appear to be adequate for design purposes, until more information is available. The common situation of several parallel rows of collectors tends to cause a load distribution similar to that specified for sawtooth roofs in ANSI A58.1-1980/Draft. Once the drifts begin to form, the geometrical difference between rows of protruding collectors on a flat roof and a sawtooth roof begin to disappear. For the design of structural members that are normal to the rows and have spans longer than the row spacing, the sawtooth load distribution may be replaced by a uniform distribution equal to the average of the peak and valley loads.

5.2.3 Surfaces that Receive Sliding Snow

CRITERION: Surfaces located such that they would receive snow sliding from solar collectors shall resist the appropriate loads from ANSI A58.1-1980/Draft plus the sliding surcharge defined in section 5.2.1a.2.

COMMENTARY: The sliding surcharge is based partially on observation and partially on intuition. Observations confirm the existence of the load and for the limited studies conducted, the magnitude. Further studies should focus on this in order to better define the magnitude and distribution of the load.

5.3 CRITERION FOR THE SERVICEABILITY OF COLLECTOR SYSTEMS

The third basic requirement is not a structural concern, but a criterion is offered based on the findings of the studies:

CRITERION: Any collector sloped less than 50° or without a clear space below at least equal to H_c shall be designed to account for extended loss of operation due to snow cover or provision for manual removal of snow shall be made.

COMMENTARY: The criterion is really a system design guideline, and obviously depends on the probability of significant snowfall. Manual removal of snow involves consideration of dumping areas, accessibility, and the resistance of the solar components and the roof surface to damage.

5.4 GUIDELINE FOR THE SERVICEABILITY OF BUILDINGS SUPPORTING COLLECTORS

The fourth basic requirement involves more than structural concerns, and the structural concern is relatively minor, since the maximum ice loads usually occur after the maximum snow load, not simultaneously with it. The following guideline is offered:

DESIGN GUIDELINE: The ice and meltwater caused by the presence of solar collectors shall be accounted for by assuring the adequacy of the moisture barrier under adverse conditions and by avoiding details likely to promote the accumulation of large quantities of ice or likely to be damaged by the weight or expansive action of ice.

6. REFERENCES

1. Building Code Requirements for Minimum Design Loads in Buildings and Other Structures, American National Standard A58.1-1980/Draft, American National Standards Institute, New York, 1980.

2. O'Rourke, Michael J., Snow and Ice Accumulation Around Solar Collector Installations, National Bureau of Standards, GCR 79-180, August 1979.

3. Corotis, Ross B., Charles H. Dowding, Edwin C. Rossow, Snow and Ice Accumulation at Solar Collector Installations in the Chicago Metropolitan Area, National Bureau of Standards, GCR 79-181, August 1979.

4. Mellor, Malcolm, Blowing Snow, Cold Regions Science and Engineering, Part III, Section A3c, Cold Regions Research & Engineering Laboratory, November 1965.

Figure 1. Light Snow Cover on Collectors During Snowfall

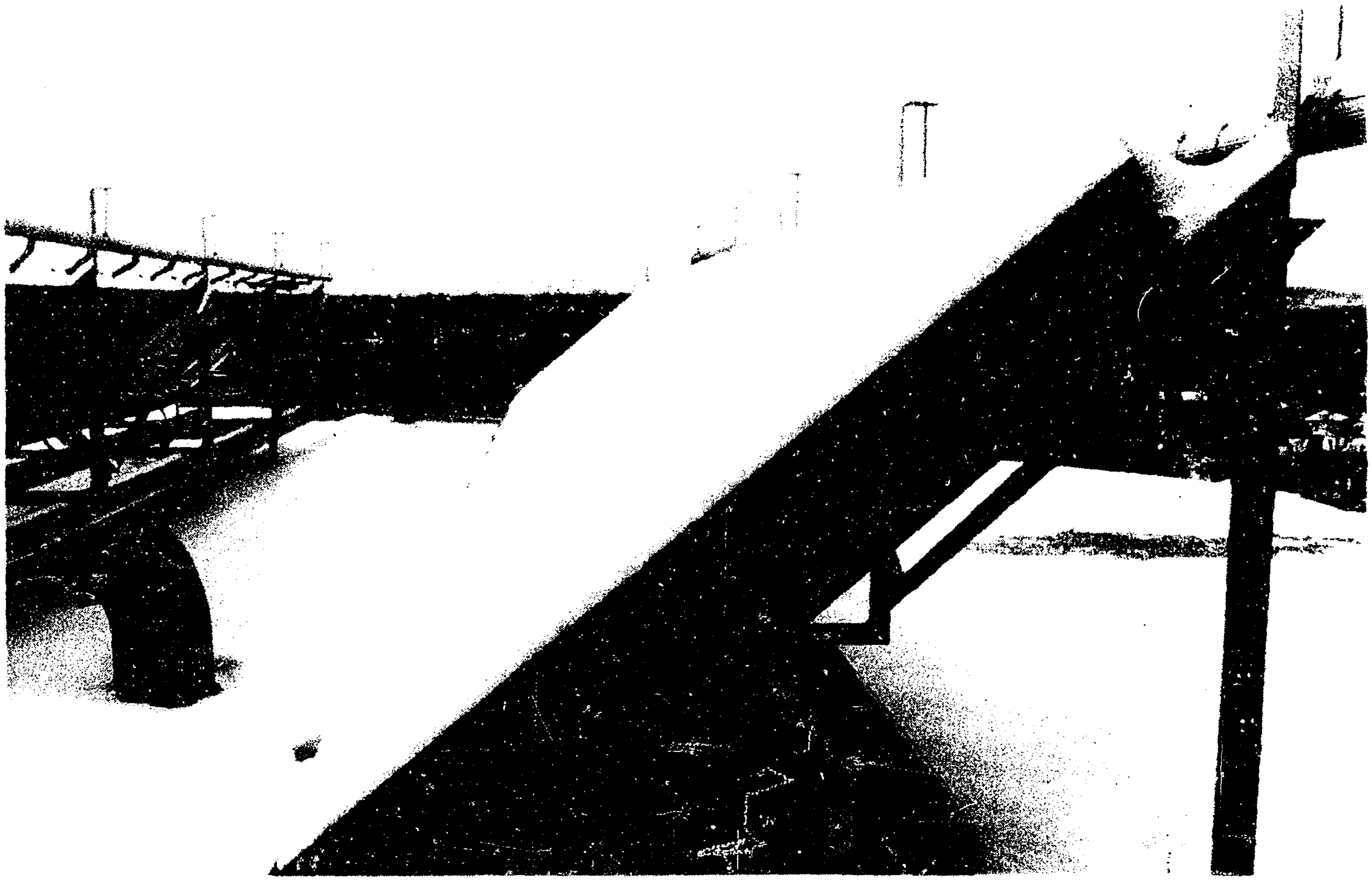


Figure 2. Light Snow Cover on Collectors After 6" Snow

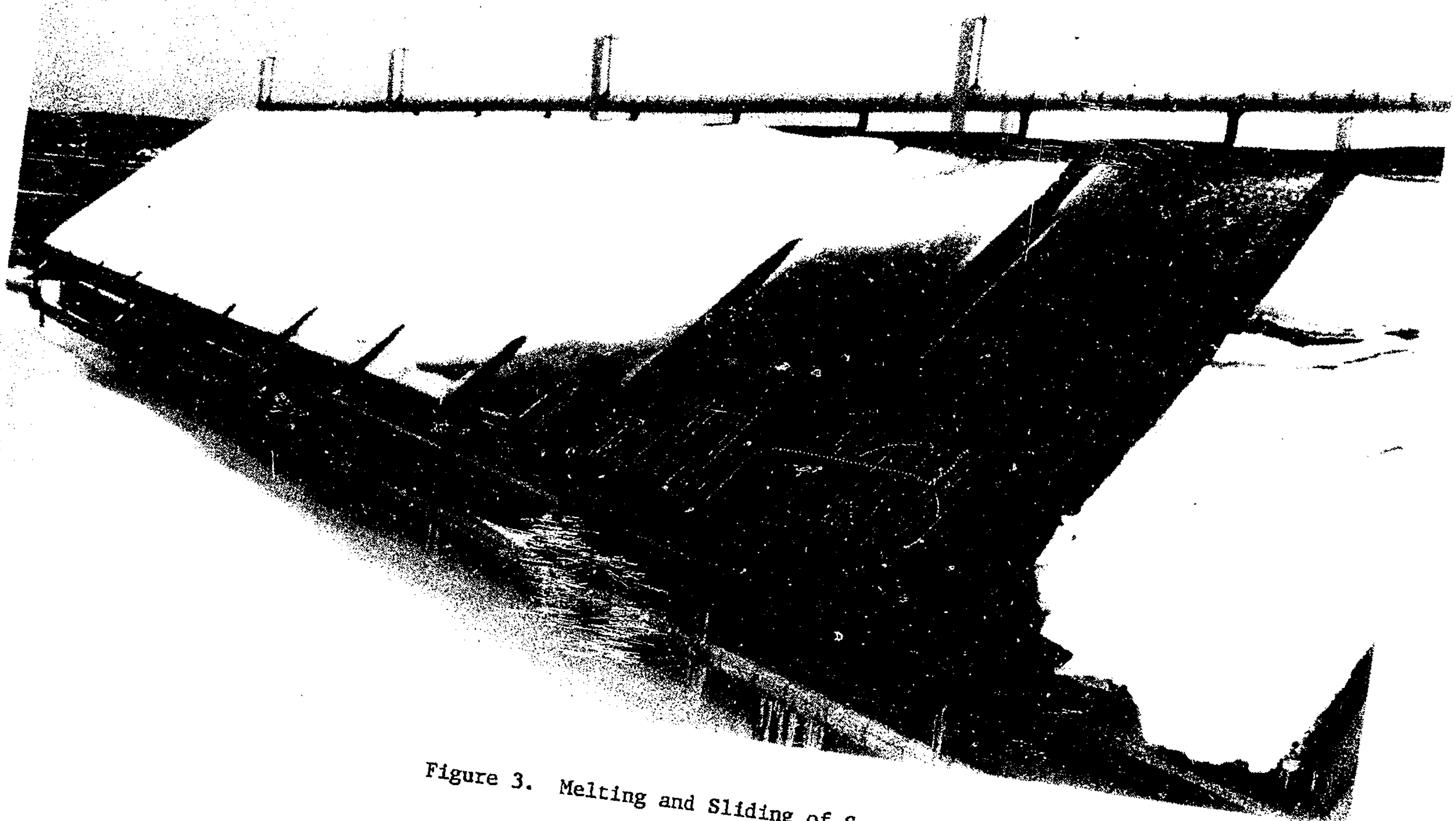


Figure 3. Melting and Sliding of Snow

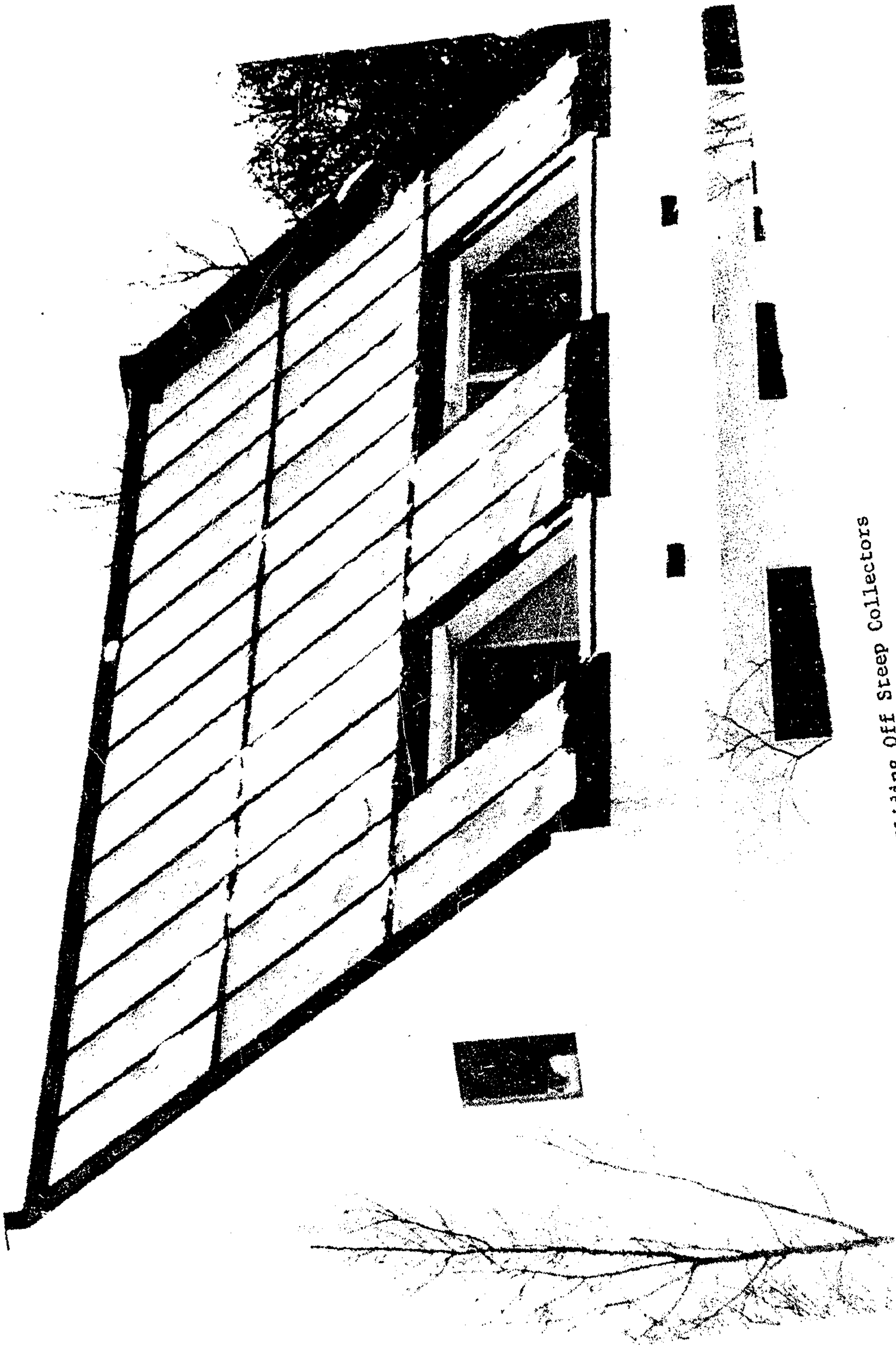


Figure 4. Snow Sliding Off Steep Collectors

Figure 5. Snow Retention on Shallow Collectors

Figure 6. Obstruction Below Steep Collectors

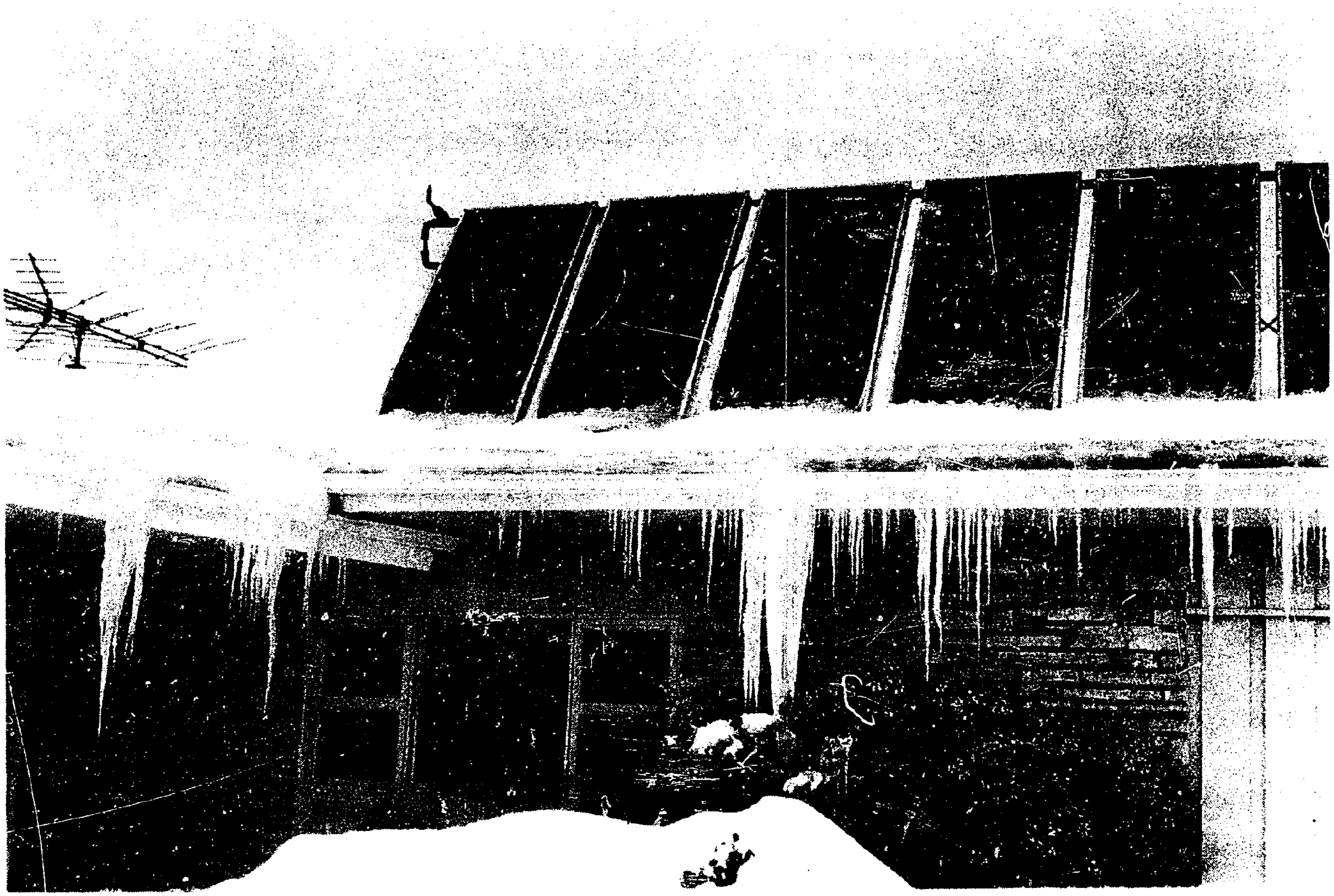


Figure 7. Ice Dam at Gutter and Icicles Below Collectors

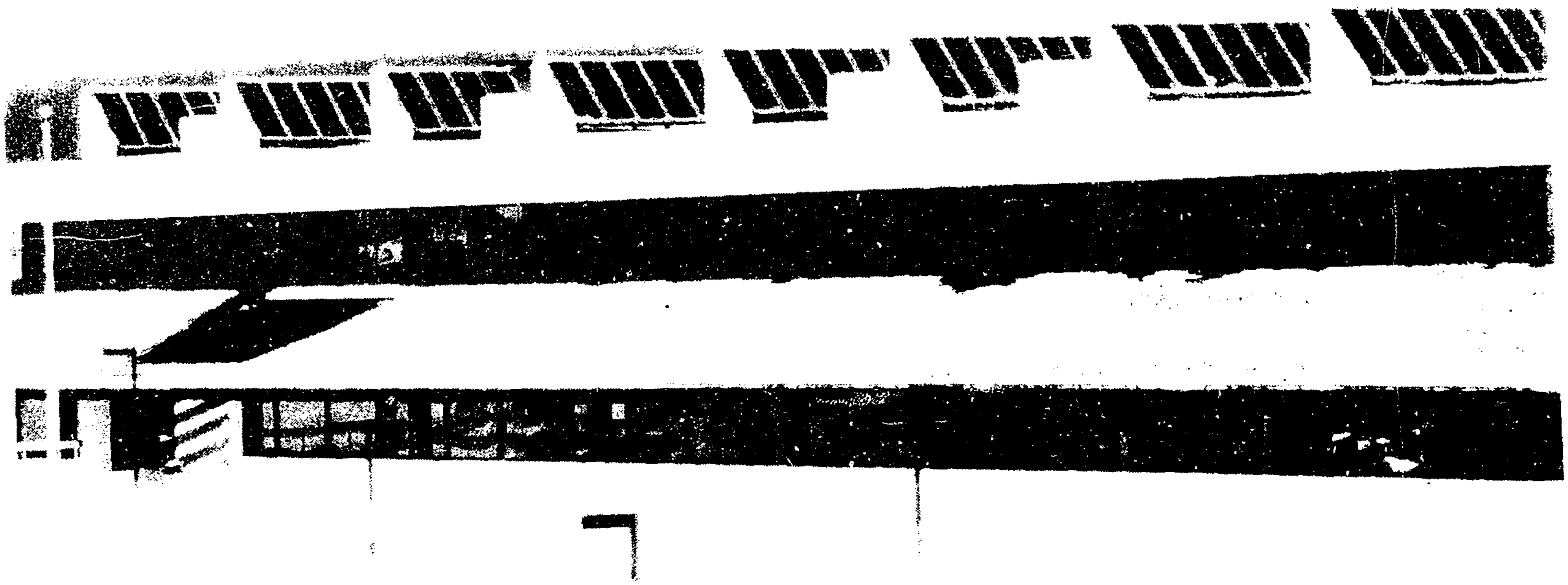


Figure 8. Building with Multiple Rows of Collectors

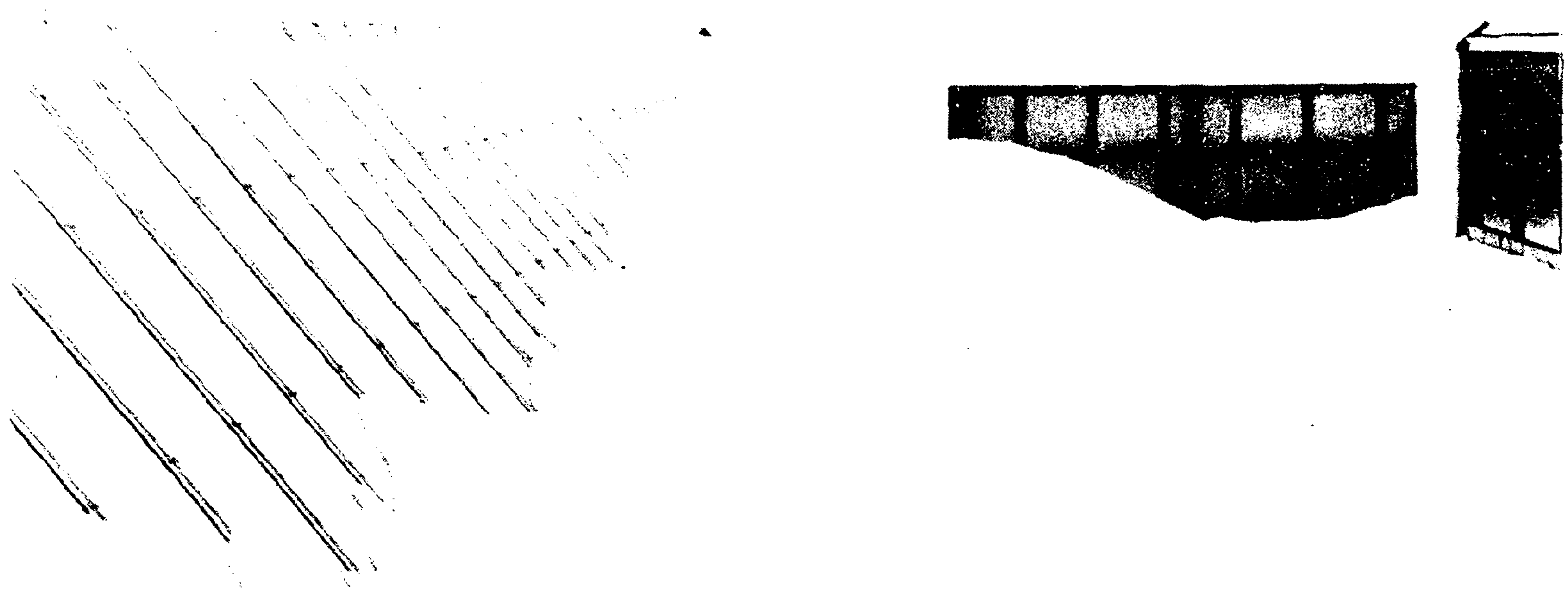


Figure 9. Drift between Parallel Rows of Collectors

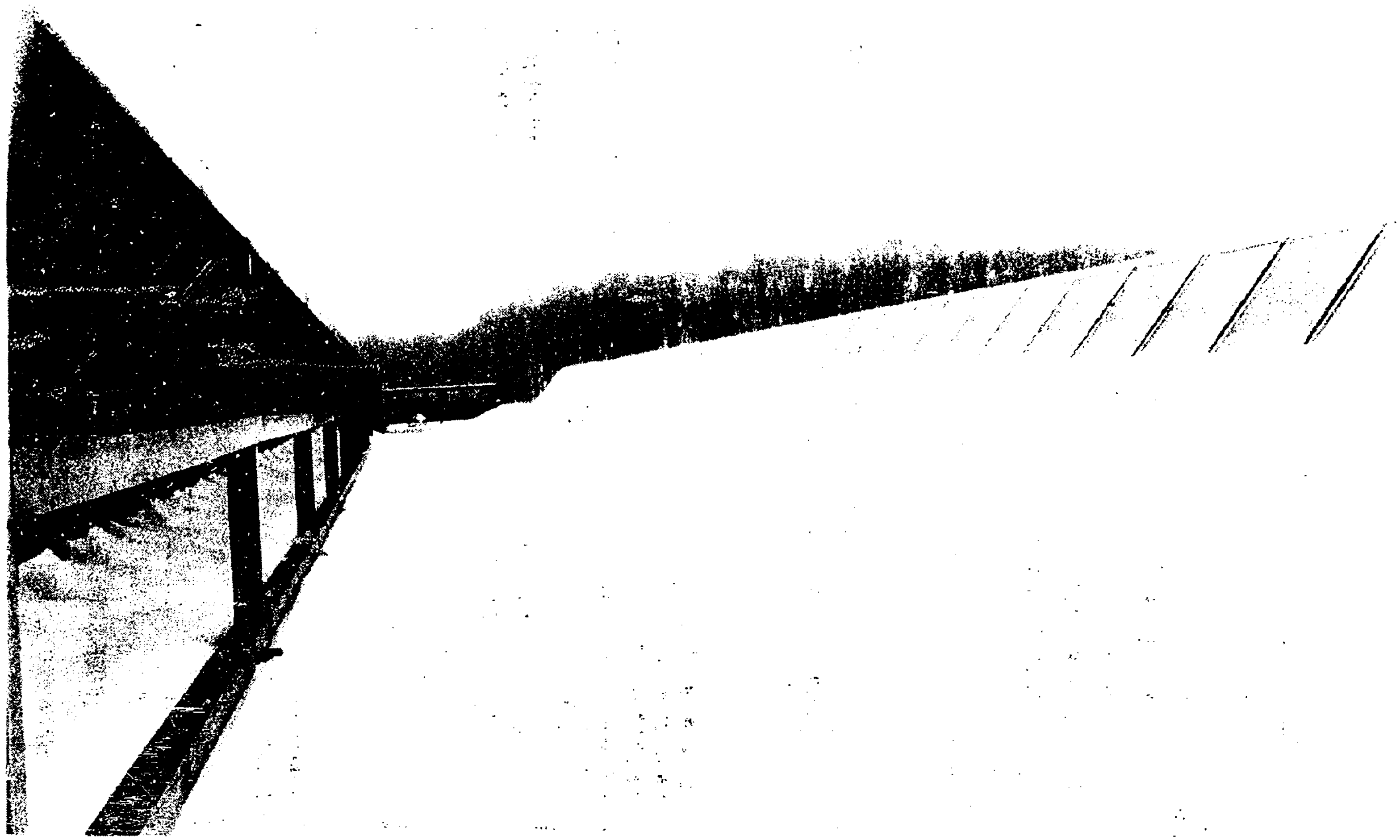


Figure 10. Drift between Parallel Rows of Collectors

FLAT ROOF SNOW LOAD, p_f

$$p_f = 0.7\ C_e\ C_t\ I\ p_g$$

WHERE:

C_e = COEFFICIENT FOR EXPOSURE TO WIND
C_t = COEFFICIENT FOR THERMAL EFFECT
I = COEFFICIENT FOR IMPORTANCE OF STRUCTURE
p_g = GROUND SNOW LOAD

SLOPED ROOF SNOW LOAD, p_s

$$p_s = C_s\ p_f$$

WHERE C_s IS DETERMINED FROM THE FOLLOWING GRAPHS (A SPECIAL EQUIVALENT SLOPE IS DEFINED FOR CURVED ROOFS)

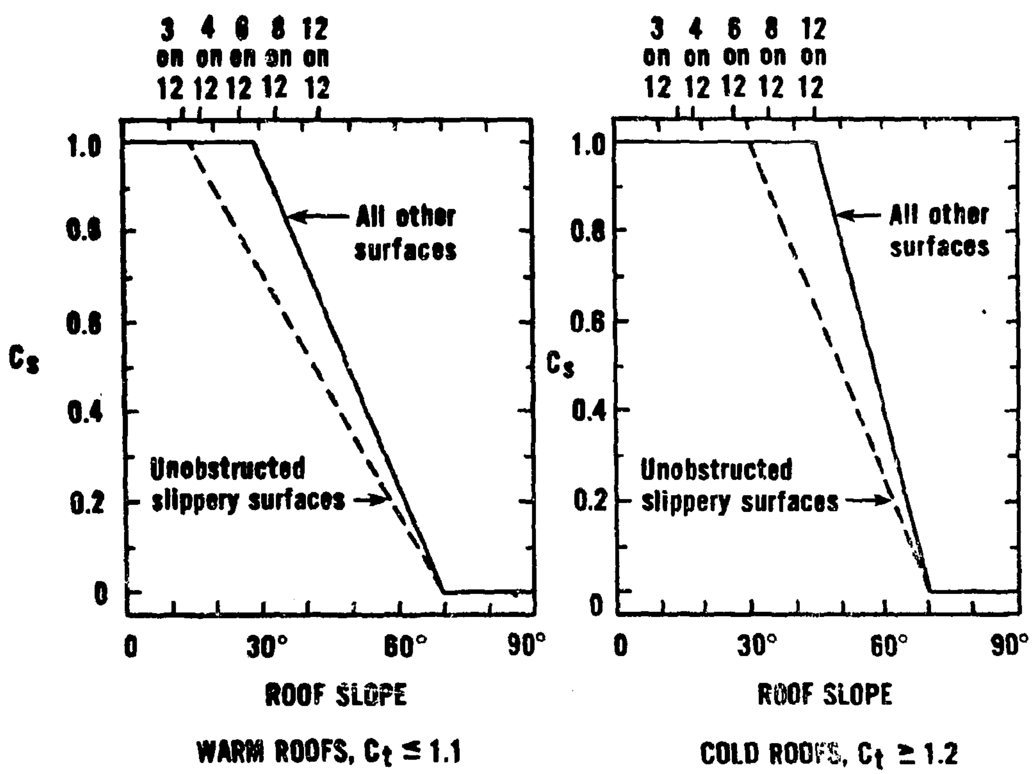
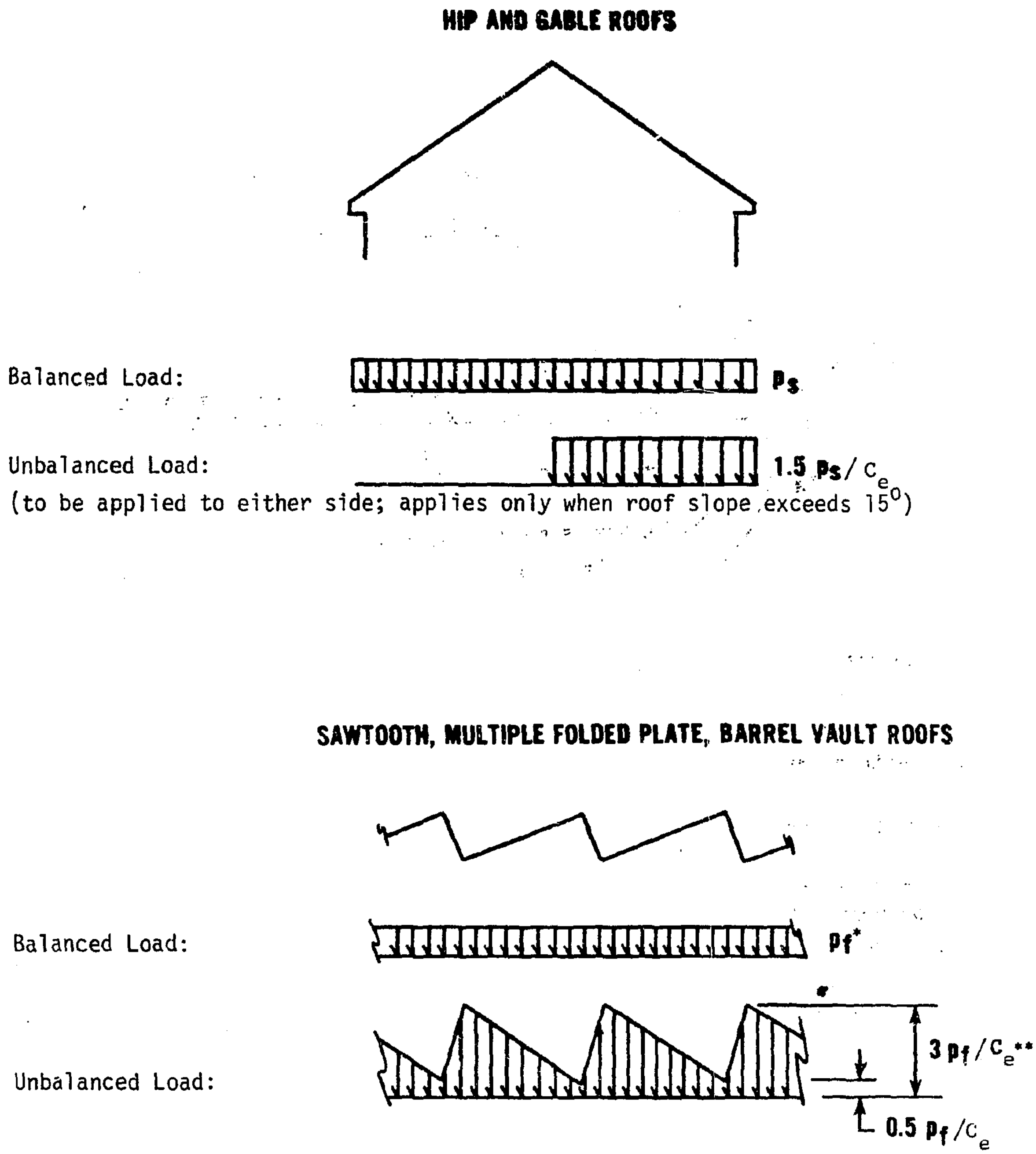


Figure 11. Basic Snow Loads, from ANSI A58.1-1980/Draft.

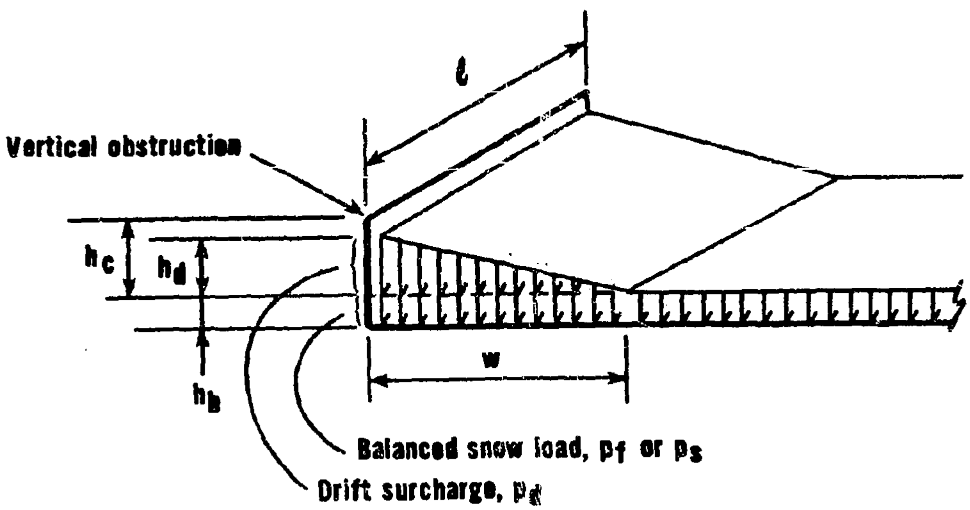


Notes:

* The slope factor C_s is defined to be 1.0 for this type of roof.

** The snow surface at the valley (assuming a density of 20pcf) need not be higher than the snow surface at the ridge, thus the peak load may be less than $3p_f/C_e$.

Figure 12. Unbalanced Snow Loads from ANSI A58.1-1980/Draft



h_b = height of balanced snow load = p_f/γ or p_s/γ

h_c = clear height from top of balanced load to top of obstruction (to edge if the obstruction is a higher roof)

h_d = depth of drift = $2\ I\ p_g\ /\ C_e\ \gamma \leq h_c$

W = width of drift = $\begin{Bmatrix} 3\ h_d \text{ for } \ell \leq 50 \text{ feet} \\ 4\ h_d \text{ for } \ell > 50 \text{ feet} \end{Bmatrix} \geq 10$ feet

if W exceeds the width of the roof, the drift surcharge shape becomes a trapezoid, truncated at the edge of the roof.

p_d = drift surcharge load = $h_d\ \gamma$

γ = snow density in pounds per square foot, per table:

p_g	under 30	30 to 60	over 60
γ	15	20	25

p_g = ground snow load, psf

Figure 13. Drift Surcharge Load from ANSI A58.1-1980/Draft

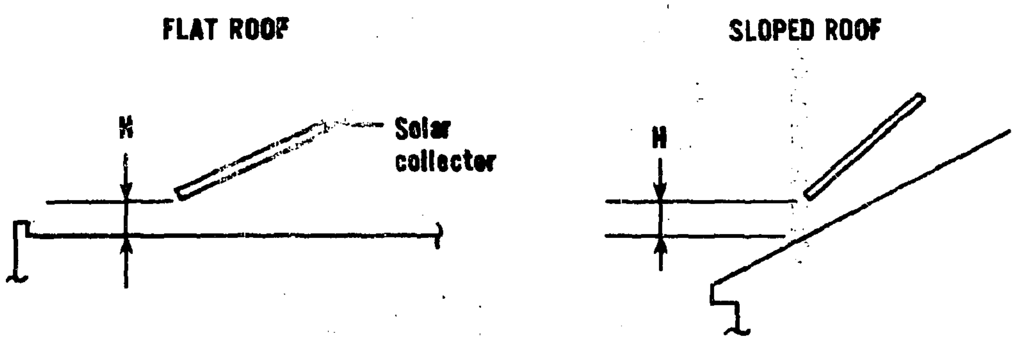


Figure 14. Definition of Clear Height H

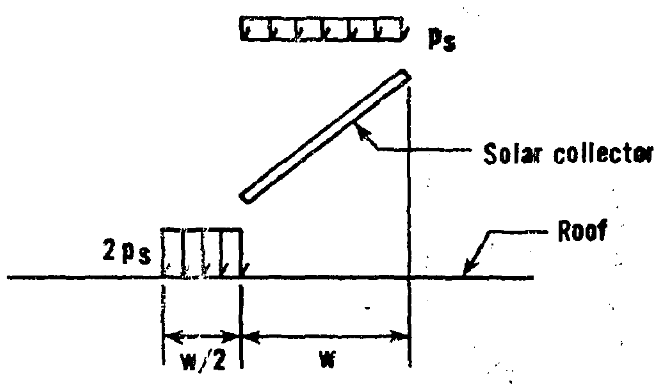


Figure 15. Definition of Sliding Surcharge

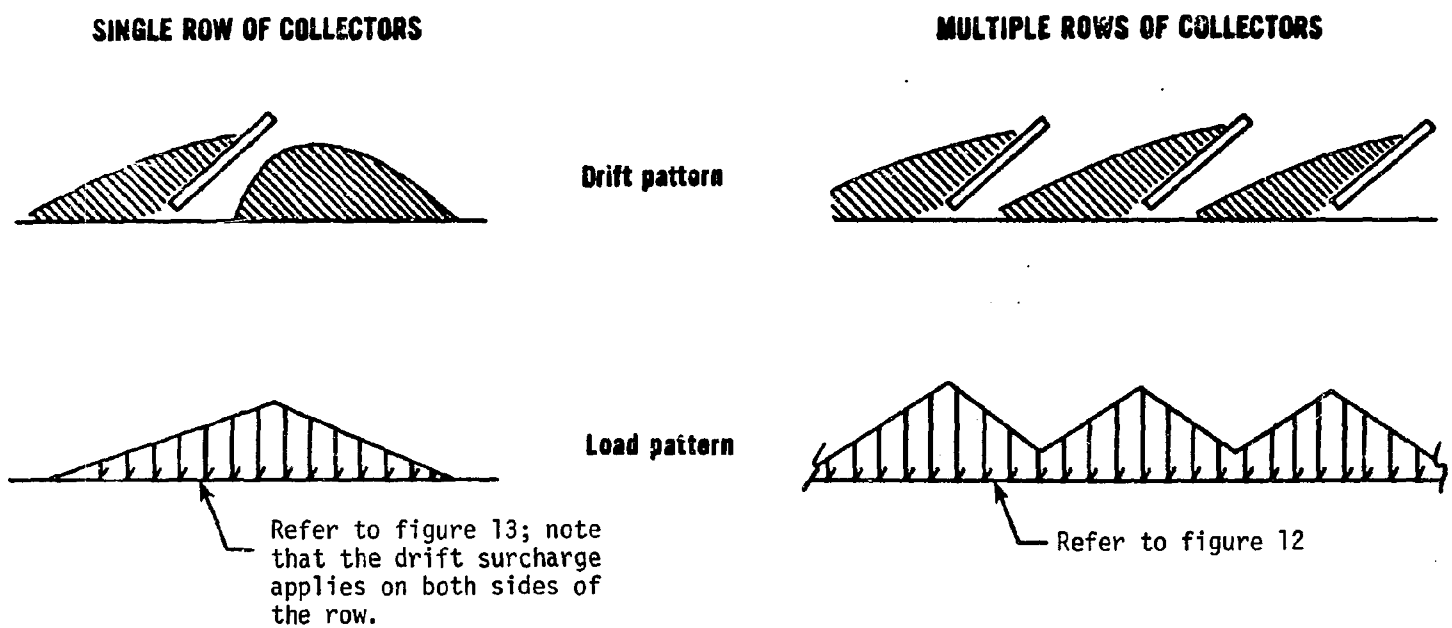


Figure 16. Load Patterns for Protruding Collectors Close to the Roof

PART IV

HAIL LOADS ON SOLAR COLLECTORS

by

Emil Simiu

and

Louis Cattaneo

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1. INTRODUCTION

This report presents proposed hail loads to be used in the design and evaluation of solar collectors exposed to hail impact. These loads are based upon information that was, in part, not available at the time of the development of earlier criteria (e.g., NBSIR 76-1187 [1]*, HUD 4930.2 [2], NBSIR 78-1562 [3]). Much of this information is included in two extensive documents devoted to hail damage risk prepared for the Department of Energy by the Jet Propulsion Laboratory (California Institute of Technology) in 1977 [4] and by Altas Corporation in 1979 [5], and in a comprehensive hail climatology review published in 1977 by S. A. Changnon, Jr. of the Illinois State Water Survey [6]. (It is noted that a large body of data and information used in reference 4 and 5 was provided by the Illinois State Water Survey.)

The proposed loads should not be regarded as definitive. Rather, by incorporating recent additional information, they represent an improvement upon the earlier criteria. However, the writers feel that uncertainties in the area of hail loading statistics continue to exist, some of them affecting the information presented herein, and that additional research is required if such uncertainties are to be reduced in the future.

Where experience indicates that the performance of solar collectors subjected to hail loads is generally satisfactory, laboratory tests for resistance to hail loads need not be conducted. Nevertheless, for cases in which previous experience is insufficient or may not be regarded as a reliable guide, laboratory testing is recommended. The information presented herein is offered for use in such testing.

2. REGIONALIZATION OF THE UNITED STATES

From the standpoint of hail damage risk, the contiguous United States is divided into three geographical regions designated as Regions I, II and III represented in figure 1. The regionalization is based on studies by Changnon and the Illinois State Water Survey [6, 7] (see also ref. 4, page 3-2). These studies have been conducted on a national scale on the basis of crop and property losses due to hail effects [6].

Further, the contiguous United States is divided into areas characterized by the average number of days with hail. This division, shown in figures 2 and 3, is based on climatological data and estimates given in ref. 7 and 8, and cited in ref. 4. For certain sections of the United States where large amounts of data make greater refinement possible, more detailed maps may be available and should be used if they are based on reliable statistical studies (e.g., [8]). (Note that the numbers in figure 3 represent the total number of days with hail in an average 20-year period and should be divided by 20 to obtain the average annual number of days with hail.)

* Numbers in brackets indicate references at the end of each part.

3. MAXIMUM HAILSTONE SIZES

Maximum sizes of hailstones assumed, for design purposes, to hit an installation depend upon: (a) geographical region, (b) average number of days with hail, (c) size of area exposed to impact, and (d) design life which, in turn, determines the mean recurrence interval of hailstone hits considered in design. It is recommended that hailstone sizes considered for design purposes correspond to a 20-year mean recurrence interval. Estimates of mean recurrence intervals of hailstone hits on a 16 sq ft (1.5-sq m) area are presented in ref. 4 (page 4-11).

According to the statistics reported in ref. 5, the estimates of ref. 4 appear to be, generally, somewhat conservative. For example, according to ref. 4, in areas with 3 days of hail per year in Region II the maximum hailstone diameter corresponding to a 20-year mean recurrence interval of hits on a 16 sq ft (1.5-sq m) exposed surface is about 1 5/8 in (41.3 mm). According to ref. 5, the maximum hailstone diameter corresponding to the same exposure classification (Albuquerque, NM) varies between 28.0 mm and 40.0 mm, depending upon the assumed hailstone size distribution used. Information on maximum hailstone sizes for various mean recurrence intervals of hits on exposed surfaces of 10 sq m, 50 sq m, and 100 sq m is found in table 3 of ref. 5.

Proposed maximum hailstone sizes corresponding to a 20-year mean recurrence interval are given in table 1. Note that the probability of occurrence of a collector hit by a given maximum hailstone size <u>and</u> of a horizontal wind speed of 66 ft/s (20.1 m/s) (see section 4.) acting in a direction perpendicular to a horizontal edge of the collector is lower than the probability of occurrence of a hit by that hailstone size regardless of horizontal wind speed and direction. This fact was taken into account in the development of table 1.

4. HAILSTONE VELOCITIES

The estimates of hailstone impact velocities listed in table 2 are given in ref. 9 in which it is assumed that the hailstones are spherical, of clear ice and have a smooth surface. These velocities represent resultants of vertical terminal velocities due to free fall [10] and an assumed horizontal velocity of 66 ft/s (20.1 m/s) due to wind speed [9,15].

5. HAILSTONE DENSITY

The specific gravity of hailstones proposed herein for design purposes is 0.9, i.e., the specific gravity of solid ice. It is believed that this proposed value for the mean specific gravity of whole hailstones (which is adopted for practicality in test procedures for the evaluation of collectors) is not overly conservative [11-13] even though lower values of local specific gravity have been measured in natural hailstones containing varying proportions of trapped air [14].

6. PROPOSED PROCEDURE FOR DETERMINING DESIGN HAIL LOADS ON SOLAR COLLECTORS

The design hail load shall be assumed to be caused by the perpendicular impact of falling hailstones with diameters and velocities specified in tables 1 and 2 (unless it can be determined on the basis of available data and statistical study that hail of smaller maximum diameter should be expected to occur). The diameters listed in table 1 are given as functions of hail region and number of days with hail as determined from maps shown in figures 1 and 2 or 3, respectively. The velocities are given in table 2 as a function of hailstone diameter. The specific gravity of hailstones shall be assumed to be 0.9.

Evaluation will be based on analysis using known information about the physical characteristics of the system components or on physical simulation and testing using appropriate hail resistance test techniques or the hail resistance test techniques described in ref. 15.

In cases where protective measures are provided to prevent impact of hail on system components, such as the use of screens or deflectors, these protective measures shall be included in the test specimen.

In proposing the design loads given herein, it is not intended to completely prevent punching or local cracking of nonstructural elements such as cover plates of collector panels under hail impact, but rather to control damage by keeping it at a level which would not cause a major curtailment in the functioning of the system, a premature failure, or hazards created by excessive shattering of glazed elements.

The hailstones diameters in table 1 were selected using, as a guide, the statistical studies reported in ref. 4 and 5. These diameters correspond approximately to a 20-year mean recurrence interval of a hit on a solar collector unit assumed to have an exposed area of approximately 16 sq ft (1.5 sq m), and are modified for the probability of a concurrent horizontal wind speed acting in a direction perpendicular to a horizontal edge of the collector. Calculations based on ref. 5 suggest that exposed areas of 10 sq m, 50 sq m, and 100 sq m may be expected to be hit during an average period of 20 years by at least one hailstone having a diameter larger than that specified in table 1 by a factor of approximately 1.12, 1.25 and 1.30 for the respective exposed areas. The velocities of table 2 are based on theoretical studies reported in ref. 10 and an assumed horizontal wind speed of 45 mph (72.4 km/h) cited in ref. 9 and 15.

7. ACKNOWLEDGEMENTS

The writers wish to express their appreciation to Stanley A. Changnon, Jr., Chief of the Illinois State Water Survey, for his valuable comments and suggestions.

8. REFERENCES

1. Interim Performance Criteria for Solar Heating and Cooling Systems in Commercial Buildings, NBSIR 76-1187, National Bureau of Standards, Washington, D. C. 20234, November 1976.

2. Intermediate Minimum Property Standards Supplement, Solar Heating and Domestic Hot Water Systems, HUD 4930.2, U. S. Department of Housing and Urban Development, Washington, D. C., 1977.

3. Interim Performance Criteria for Solar Heating and Cooling Systems in Residential Buildings, Second Edition, NBSIR 78-1562, National Bureau of Standards, Washington, D. C. 20234, November 1978.

4. Gonzales, C., Environmental Hail Model for Assessing Risk to Solar Collectors, JPL 5101-45, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, December 1977.

5. Cox, M. and Armstrong, P. R., A Statistical Model for Assessing the Risk of Hail Damage to Any Ground Installation, ALO/4291-1, Altas Corporation, Santa Cruz, CA 95060, September 1979.

6. Changnon, S. A., "The Scales of Hail," Journal of Applied Meteorology, Vol. 16, No. 6, June 1977.

7. Farhar, B. C., Changnon, S. A., Swanson, E. R., Davis, R. J., and Haas, J. E., Hail Suppression and Society, Illinois State Water Survey, Urbana, IL, June 1977.

8. Stout, G. E. and Changnon, S. A., Climatography of Hail in the Central United States, CHIAA Research Report No. 38, Crop Hail Insurance Actuarial Association, Chicago, IL 60606, February 1968.

9. Mathey, R. G., Hail Resistance Tests of Aluminum Skin Honeycomb Panels for the Relocatable Lewis Building, Phase II, NBS Report 10193, National Bureau of Standards, Washington, D. C. 20234, April 1970.

10. Bilham, E. G. and Relf, E. F., "The Dynamics of Large Hailstones," Quarterly Journal of the Royal Meteorological Society, Vol. 63, pp. 149-162, 1937.

11. Macklin, W. C., Strauch, E., and Ludlam, F. H., "The Density of Hailstones Collected from a Summer Storm," Nubila, Vol. 3, pp. 12-17, 1960.

12. Browning, K. A., Ludlam, F. H., and Macklin, W. C., "The Density and Structure of Hailstones," Quarterly Journal of the Royal Meteorological Society, Vol. 89, No. 379, 1963.

13. List, R., Cantin, J. G., and Ferland, M. G., "Structural Properties of Two Hailstone Samples," Journal of the Atmospheric Sciences, Vol. 27, pp. 1080-1090, October 1970.

14. Prodi, F., "Measurements of Local Density in Artificial and Natural Hailstones," Journal of Applied Meteorology, Vol. 9, No. 6, 1970.

15. Jenkins, D.R. and Mathey, R.G., Hail Impact Testing of Solar Collector Covers, NBS report in preparation, National Bureau of Standards, Washington, D.C., 20234.

9. BIBLIOGRAPHY

Arenberg, D. L., "The Formation of Small Hail and Snow Pellets," Bulletin American Meteorological Society, Vol. 22, No. 3, 1941.

Auer, A. H., "Distribution of Graupel and Hail with Size," Monthly Weather Review, Vol. 100, No. 5, 1972.

Bailey, I. H. and Macklin, W. C., "The Surface Configuration and Internal Structure of Artificial Hailstones," Quarterly Journal of the Royal Meteorological Society, Vol. 94, No. 399, 1968.

Baldwin, J. L., Climates of the United States, National Oceanic and Atmospheric Administration, Washington, D. C., 1973.

Changnon, S. A., "Method of Evaluating Substation Records of Hail and Thunder", Monthly Weather Review, Vol. 95, No. 4, 1967.

Changnon, S. A., "Note on Hailstone Size Distributions", Journal of Applied Meteorology, Vol. 10, No. 2, 1971.

Changnon, S. A., Solar Energy Information and Data for Illinois, Illinois State Water Survey, Urbana, IL, 1978.

Changnon, S. A., Farhar, B. C. and Swanson, E. R, "Hail Suppression and Society", Science, Vol. 200, No. 4340, 1978.

Changnon, S. A., and Morgan, G. M., Design of an Experiment to Suppress Hail in Illinois, Illinois State Water Survey, Urbana, IL, 1976.

Clift, R., Bubbles, Drops, and Particles, Academic Press, New York, NY, 1978.

Eng Young, R. G. and Browning, K. A., "Wind Tunnel Tests of Simulated Spherical Hailstones with Variable Roughness", Journal of the Atmospheric Sciences, Vol. 24, No. 1, 1967.

Foote, G. B. and Knight, C. A., Eds., Hail: A Review of Hail Science and Hail Suppression, (Meteorological Monographs Vol. 16, No. 38), American Meteorological Society, Boston, MA, 1977.

Friedman, D. G., Texas Hailstorms, Research Department Report, The Travelers Insurance Companies, Hartford, CT, 1965.

Friedman, D. G. and Shortell, P. A., Prospective Weather Hazard Rating in the Midwest with Special Reference to Kansas and Missouri, Research Department Report, The Travelers Insurance Companies, Hartford, CT, 1967.

Gokhale, N. R., Hailstorms and Hailstone Growth, State University of New York Press, Albany, NY, 1975.

Greenfeld, S. H., Hail Resistance of Roofing Products, Building Science Series, No. 23, National Bureau of Standards, Washington, D.C. 20234, 1969.

Gringorten, I. I., Hailstone Extremes for Design, AFCRL-72-0081, Air Force Cambridge Research Laboratories, Bedford, MA, 1971.

Harting, A., The UTIAS Precipitation Wind Tunnel, Technical Note No. 181, Institute for Aerospace Studies, University of Toronto, Canada, 1972.

Hoerner, S. F., Fluid-Dynamic Drag, Published by the author, Midland Park, NJ, 1958.

Houghton, H. G., "On the Physics of Clouds and Precipitation," Compendium of Meteorology, Ed.: Malone, T. F., American Meteorological Society, Boston, MA, 1951.

Imperial College of Science and Technology (London), Final Report: Research on Characteristics and Effects of Severe Storms, AFCRL-64-531, Air Force Cambridge Research Laboratories, Bedford, MA, 1964.

Knight, C. A. and Knight, N. C., "The Falling Behavior of Hailstones", Journal of the Atmospheric Sciences, Vol. 27, July 1970.

Knight, C. A. and Knight, N. C., "Hailstones", Scientific American, Vol. 224, No. 4, 1971.

Laurie, J. A. P., Hail and ITrmEffects on Buildings, Bulletin 21, National Building Research Institute, Pretoria, South Africa, 1960.

List, R., The Aerodynamics of Hailstones, Research Transl. TG-244, (Z. Angew. Math. Phys., Vol. 10, No. 2, pp. 143-159, 1959), Air Force Cambridge Research Laboratories, Bedford, MA, September 1965.

Löf, G. O. G. and French, R. R., Hail Resistance of Solar Collectors with Tempered Glass Covers, Preprint: SERI Conference at Colorado Springs on Solar Heating and Cooling Systems, Solar Energy Research Institute, Golden, Colorado, November 1979.

Ludlam, F. H., "The Hail Problem", Nubila, Vol. 1, pp. 12-96, 1958.

Macklin, W. C. and Bailey, I. H., "On the Critical Liquid Water Concentrations of Large Hailstones", Quarterly Journal of the Royal Meteorological Society, Vol. 92, No. 392, 1966.

Macklin, W. C. and Ludlam, F. H., "The Fallspeeds of Hailstones," Quarterly Journal of the Royal Meteorological Society, Vol. 87, No. 371, 1961

McDonald, J. E., "An Aid to Computation of Terminal Fall Velocities of Spheres", Journal of Meteorology, Vol. 17, pp. 463-465, 1960.

Moore, D. and Wilson, A., Photovoltaic Solar Panel Resistance to Simulated Hail, Report 5101-62, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, October 1978.

Morgan, G. M. and Towery, N. G., Micro-Scale Studies of Surface Hailfall, Final Report, Illinois State Water Survey, Urbana, Il., March 1974.

Morgan, G. M. and Towery, N. G., "On the Role of Strong Winds in Damage to Crops by Hail and Its Estimation with a Simple Instrument", Journal of Applied Meteorology, Vol. 15, No. 8, 1976.

Piat, D., "Etude Experimentale des Grelons en Chute Libre", Journal de Mecanique et de Physique de L'Atmosphere, Series II, Vol. 4, No. 13, 1962.

Prodi, F., "X-Ray Images of Hailstones", Journal of Applied Meteorology, Vol. 8, June 1969.

Roos, D. v. d. S., "A Giant Hailstone from Kansas in Free Fall", Journal of Applied Meteorology, Vol. 11, September 1972.

Roos, D. v.d. S. and Carte, A. E., "The Falling Behaviour of Oblate and Spiky Hailstones," Journal de Recherches Atmospheriques, pp. 39-52, 1973.

Schlichting, H., Boundary Layer Theory, 7th Ed., McGraw Hill, New York, NY, 1979.

Schumann, T. E. W., "The Theory of Hailstone Formation", Quarterly Journal of the Royal Meteorological Society, Vol. 64, pp. 3-21, 1938.

Smith, M. L., Hail Testing of Solar Reflector Panels, Preprint: Workshop at Denver on Solar Reflector Materials Technology, Texas Tech University, Lubbock, TX, 1978.

Thom, H. C. S., "The Frequency of Hail Occurrence", Archiv für Meteorologie, Geophysik und Bioklimatologie, Series B, Vol. 8, No. 2, 1958.

Towery, N. G., Changnon, S. A. and Morgan, G. M., "A Review of Hail-Measuring Instruments", Bulletin of the American Meteorological Society, Vol. 57, No. 9, 1976.

Towery, N. G., Morgan, G. M. and Changnon, S. A., "Examples of the Wind Factor in Crop-Hail Damage", Journal of Applied Meteorology, Vol. 15, No. 10, 1976.

Willis, J. T., Browning, K. A., and Atlas, D., "Radar Observations of Ice Spheres in Free Fall," Journal of the Atmospheric Sciences, Vol. 21, No. 1, 1964.

Table 1. Diameter of Expected Maximum Size Hailstone as a Function of Geographical Region and Days with Hail Per Year.*

Days with Hail per year	Diameter of Expected Maximum Size Hailstone, inches (mm)		
	Region III	Region II	Region I
1	7/8 (22.2)	1 1/8 (28.6)	1 (25.4)
3	1 (25.4)	1 1/4 (31.8)	1 (25.4)
5	1 1/8 (28.6)	1 3/8 (34.9)	
9	1 1/2 (38.1)	1 1/2 (38.1)	

* For 20-year mean recurrence interval

Table 2. Design Hailstone Velocities

Hailstone Diameter, inches (mm)	Resultant Velocity*, ft/s (m/s)
7/8 (22.2)	95 (29.0)
1 (25.4)	98 (29.9)
1 1/8 (28.6)	101 (30.8)
1 1/4 (31.8)	105 (32.0)
1 3/8 (34.9)	108 (32.9)
1 1/2 (38.1)	112 (34.1)

* Resultant of terminal vertical velocity and horizontal velocity of 66 ft/s (20.1 m/s) [9]

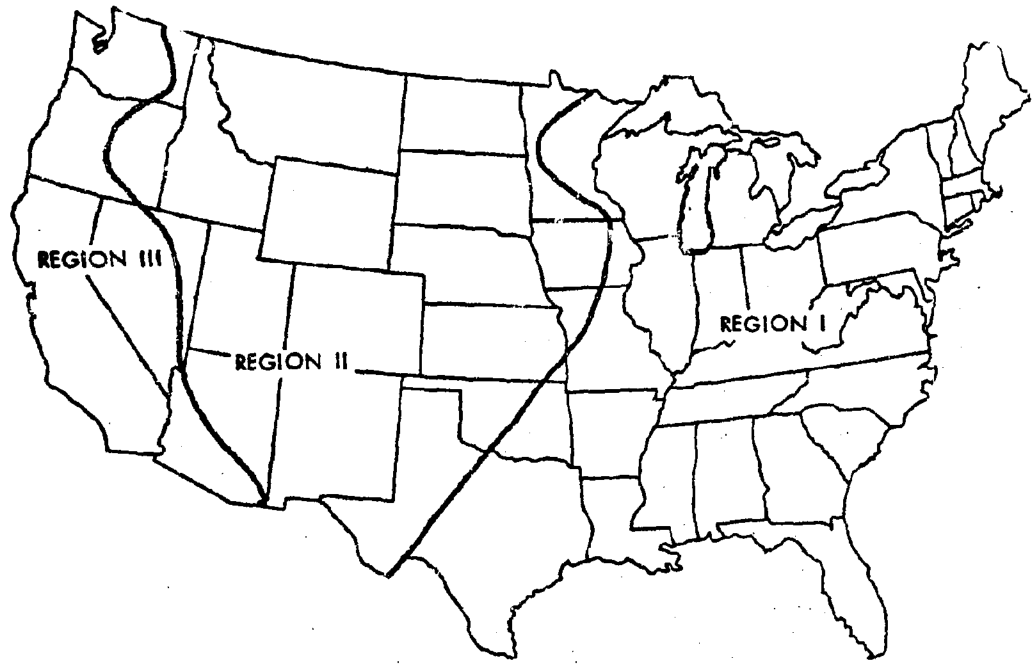

Figure 1. Hail Regions (Ref. 4)

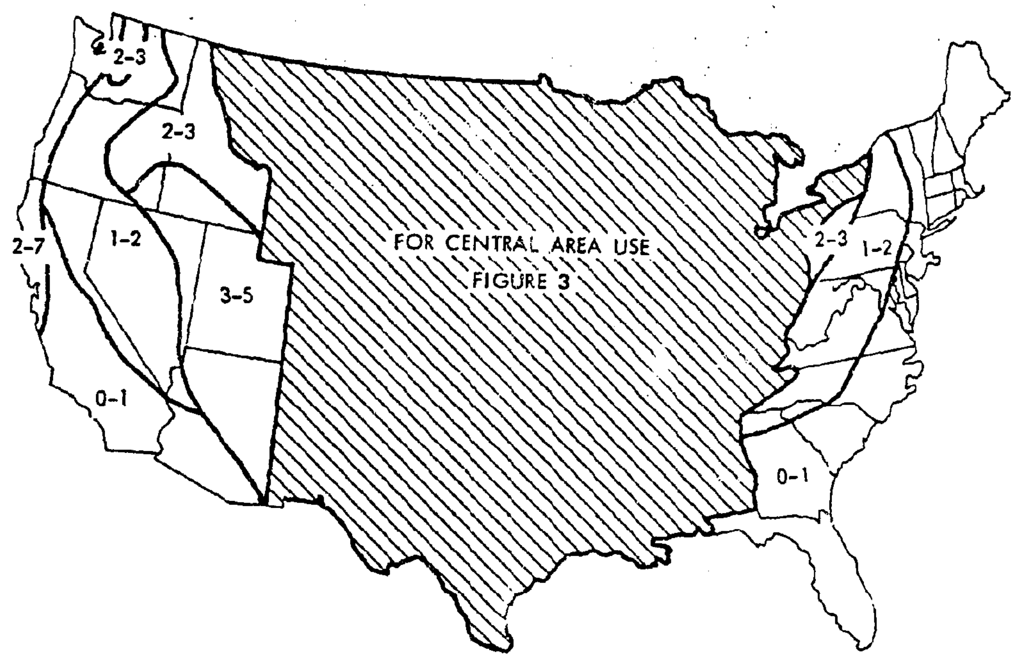

Figure 2. Average Annual Number of Days with hail (Ref.)

Note: Numbers on this map should be divided by 20 to obtain the average annual number of days with hail.

Figure 3. Total Number of Days with Hail in an Average 20-year Period for the Central United States (Ref. 8)