STRUCTURAL SNOW LOADS

By

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INTRODUCTION

Snow load is the governing criterion for roof design in many regions of the United States. This is of concern to engineers charged with the public welfare and performance of buildings. Historically, snow loads and rain on inadequately drained roofs have each caused about the same number of roof collapses, with the associated dollar losses approximately equal for both causes. Recently, snow-related collapses have exceeded those due to rain because of unusually heavy snowfalls in the United States. This can be confirmed by studying the statistics on roof collapses gathered by Factory Mutual Insurance Company, the insurer of approximately 60 percent of the industrial buildings in the United States. They report that from 1974 to 1978 roof losses were caused by: snow loads (55 percent); rain (20 percent); and miscellaneous effects such as structural deterioration and excessive equipment loads (25 percent). These facts indicate the waste of natural resources and danger to human life represented by snow loads.

FACTORS AFFECTING ROOF SNOW LOADS

The snow load on a structure is influenced by (1) the basic ground snow load for the site, and (2) factors affecting depth, density, and distribution of snow on the roof. Lake Tahoe was the first area in the United States to define regional ground snow loads, and subsequent studies were done for the states of Alaska, Arizona, Colorado, Idaho, Michigan, Montana, Oregon and Washington.

Structural snow loads can be calculated by multiplying the ground snow loads by a coefficient that reflects both the building shape and other effects such as wind exposure. This approach was initially suggested by the National Research Council of Canada, and these ground-to-roof conversion factors were obtained from an extensive program involving field observations, practical experience and engineering judgement. The results of this study are contained in the present National Building Code of Canada. The American National Standards Institute used these same conversion factors in their 1972 standard (ANSI A58.1-1972). In the snow load criteria for Alaska, it is suggested that snow loads on roofs are affected by local winds and temperatures, the exposure of the roof to wind, as well as the roof's thermal characteristics and geometry (Tobiasson and Redfield, 1973). It was proposed that the basic roof snow load be obtained by multiplying the ground snow load by three dimensionless coefficients; one each for regional, thermal and exposure effects.

In 1975 the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) initiated a study of roof snow loads at eight locations across the country. Data for 199 structures were accumulated for three winters beginning with 1975-76 in the states of Colorado, Idaho, Michigan, New York, Oregon and South Dakota. Analysis of the data (O'Rourke and Redfield, 1980) indicated that the range of values for the exposure coefficient in the Alaska study was reasonable; however, it failed to provide concise information about the effects of thermal characteristics and slope of the roofs, since 75 percent of the roofs were in only one of the four thermal categories. In addition, only 20 percent of the structures had slopes greater than 30 percent; i.e., the geometry where slope effects become significant.

SNOW LOADS FROM ANSI A58.1-1982

In 1978 ANSI established a snow load subcommittee with membership from the industrial, governmental and academic communities to study and formulate revisions for the new standard (ANSI A58.1-1982). This subcommittee used the Alaska study and the CRREL information as a data base and recommended that the roof snow load on an unobstructed flat

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roof for the contiguous United States to be

$$p_f = 0.7C_eC_tIp_g \tag{1a}$$

and for Alaska,

$$p_f = 0.6C_eC_tIp_g \tag{1b}$$

where p_f is the flat-roof design snow load and p_g the site-specific ground snow load, both quantities are in pascals. The values for the dimensionless factors C_e (exposure) and C_t (thermal) are presented in Tables 1 and 2, respectively.

Table 1

Exposure Factor, C_e From ANSI A58.1-1982

Site Description	C_e
Windy with roof exposed on all sides and no shelter afforded by terrain, etc.	0.8
Windy with little shelter	0.9
Discontinuous snow removal by wind because of terrain, etc.	1.0
Little wind with terrain, etc. to shelter roof	1.1
Densely forested with little wind, and roof located in among conifers	1.2

Table 2

Thermal Factor, C_t From ANSI A58.1-1982

Thermal Condition of Structure	C_t
Heated	1.0
Heated just above freezing	1.1
Unheated	1.2

The building importance factor I is 0.8 for agriculture buildings, 1.2 for essential facilities, 1.1 for buildings with more than 300 people in one area, and 1.0 for all other structures. The fact that snow is not totally retained on a sloped roof is accounted for by computing the sloped roof snow load p_s as follows:

$$p_s = C_sp_f \tag{2}$$

where the roof slope factor C_s depends upon whether the roof is warm or cold, the slope of the roof and the coefficient of friction of the surface (e.g., metal is considered slippery and composition shingle roofs are not). In addition, values of C_s for various roof configurations, e.g., curved and vaulted, are prescribed. Procedures are also described for calculating the effects of unloaded roof portions, unbalanced snow load, drifting snow, sliding snow, and the additional load from rain on snow.

FIELD STUDY OF BUILDING THERMAL EFFECTS

The objective of a study initiated in 1982 at the University of Idaho was to examine C_t in Eq. (1). A test structure was identified in deep-snow country that had multiple thermal environments so that thermal effects could be measured independently of other factors such as wind environment, roof slope, etc. The single story building is approximately 18 by 53 m, with a roof 4 by 18 m protruding over an open loading dock (see Fig. 1).

USDA-FOREST SERVICE WAREHOUSE

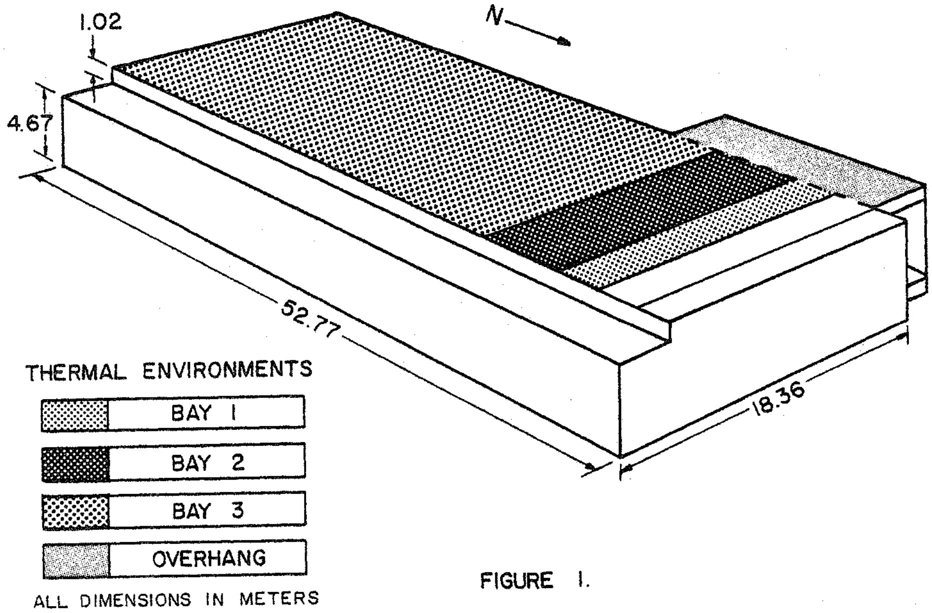


FIGURE 1.

The test structure is situated in a relatively sheltered location surrounded by coniferous trees and other buildings so that the roof and ground snow experience the same wind and convection environments. That is C_e = 1.0 from Eq. (1).

Building

The structure is a warehouse which has a nominally flat roof (slope = 0.01), and the interior is divided into two distinct thermal environments. The north 20 m are used as an office and staging area with the temperature maintained at 18 to 21°C, while supplies and equipment are stored in the south 33 m where the temperature ranges from 13 to 16°C. In one bay of the heated area, 230 mm of fiberglass insulation was installed. Thus, in one building we have four thermal roof environments: (1) the heated and newly insulated area (bay 1); (2) the heated office area (bay 2); (3) the warehouse area with low heat (bay 3); and (4) the outside dock roof which is unheated (overhang). The characteristics of these are summarized in Table 3.

Climatology

The test structure is located in McCall, Idaho (Sec. 8 and 9; T18N; R3E; elev. 1532 m), which is situated at the south end of Payette Lake and is flanked by the north-south-trending mountains of the Payette-Salmon Divide (elev. 1525 to 2745 m). The area receives 3.36 m of snow annually with an average water content of 340 mm (Rice, 1970), and the average maximum ground snow depth is 1.10 m. The maximum expected ground snow depth with a 30 year recurrence interval for the area is 1.70 m with a water content of 652 mm (Rusten, 1976), and the regional wind speed with a 25 year recurrence interval is 48 km/h (Smith, 1980).

During the test period from November, 1982 to March 11, 1983, McCall received 3.09 m of snow with a water equivalent of 440 mm, and a maximum ground snow depth of 1.14 m. During this period, extreme temperatures ranged from -23°C to 13°C, with an average of -1°C. The wind speed for the observation period averaged 2.82 km/h.

Table 3

Summary of Thermal Environments

Property \ Location	Bay 1	Bay 2	Bay 3	Overhang
R§--(°C·m²)/W (°F·hr·ft²)/BTU	6.15 (35.0)	0.872 (4.95)	0.872 (4.95)	0.872 (4.95)
Inside Temp--°C (°F)	18 (65)	18 (65)	14 (58)	* (*)
Heat Flux--W/m²† [BTU/(hr·ft²)]	0.476 (1.50)	1.49 (4.71)	0.903 (2.85)	0 (0)

§Thermal conductivity of roof structure

*Same as outside air temperature

†Mean values (December 29, 1982 to March 11, 1983)

Instrumentation

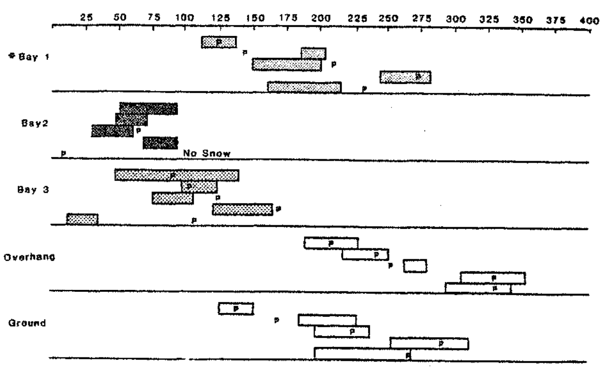
A bay in thermal environments 1, 2, and 3 were instrumented as follows: three copper-constantan thermocouples placed at the top, middle and bottom of the beams for air temperature; a square (114 mm) heat flux transducer (Thermonetrics Corp., Model H11-18-1-SHF, series S418) placed on the ceiling near the center of each monitored bay. An additional copper-constantan thermocouple was placed outside the building on a beam underneath the overhang for outside temperature. On January 27 additional copper-constantan thermocouples were placed on the roof under the snow in thermal environments 1, 2 and 3 to monitor roof-snow interface temperature. Wind speed and direction were monitored using a Weathertronics Model 2112 Stratavane wind sensor mounted on a 4.57-m tower attached to the roof. All transducers were continuously monitored by a Hewlett Packard Model HP3497/HP85 data acquisition system located inside the building. Between December 29, 1982 and March 11, 1983, all the instruments were read every five minutes, and these point readings were averaged over a six-hour period. The mean, standard deviation, and skewness were computed for the instruments for each six-hour period and recorded on magnetic tape by the HP 85F controller.

DATA COLLECTION

Daily records of depth and water content of the newly fallen snow, depth of snow on the ground, cloud cover at the time of the precipitation readings and a continuous record of relative humidity were obtained from the McCall National Weather Service (NWS) station No. 10 5708-4. The site where these data were obtained is approximately 30 m from the test structure. Daily water content for the precipitation was distributed over the four six-hour periods according to the times reported by NWS. Using the procedures outlined by Linsley et al (1975), the atmospheric vapor pressure and dew point were estimated by combining the average six-hour readings for relative humidity with the average outside air temperature at the building test site. The cloud cover for the entire day was assumed to be the same as that reported at the time of the precipitation readings (1800 mst).

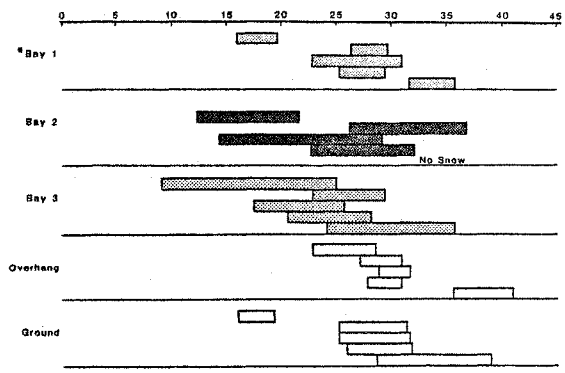
On five occasions during the test period, snow core samples were taken from the ground and the roof at each of the four thermal environments to determine the snow depth, water content and density. At each sampling location, six vertical core samples were taken from a 0.30-m square using a Mt. Rose snow sampler. Standard data reduction procedures were used. The mean, standard deviation, standard error of the mean, and the 95 percent confidence interval for the standard error of the mean were calculated for each parameter for the aggregate of the six samples at each location (see Figs. 2 and 3).

Figure 2. MEASURED WATER CONTENT (mm)



* The five bars from top to bottom for each group represent sampling dates of 12/29/82, 1/27/83 and 2/5/83, 2/19/83 and 3/11/83, respectively. Bar lengths are the range of values for the 95 percent confidence level for the standard error of the mean. P Predicted

Figure 3. MEASURED SNOW DENSITY (%)



*The five bars from top to bottom for each group represent sampling dates of 12/29/82, 1/27/83 and 2/5/83, 2/19/83 and 3/11/83, respectively. Bar lengths are the range of values for the 95 percent confidence level for the standard error of the mean.

<u>SNOW MELT MODEL</u>

In order to estimate the change in snow pack water content for periods between snow samples, a melt model was developed based on a standard energy balance (Viessman, et al, 1977)

$$H_m = H_{rl} + H_{rs} + H_c + H_e + H_f + H_p + H_q \tag{3}$$

and

$$M = H_m/Q \tag{4}$$

where

H_m = heat equivalent of the snow; kJ/m^2(SI), BTU/ft^2(USCS)

H_{rl} = net long wave radiation exchange between the snow pack and the surroundings

H_{rs} = absorbed solar radiation

H_c = convective melt from the air

H_e = heat added or removed due to condensation or sublimation

H_f = heat flux conducted from a warm surface

H_p = rainfall heat content

H_q = internal energy change in the snow pack

M = depth of water melted; mm (SI), in (USCS)

Q = heat of fusion (quantity of heat required to melt a unit volume of ice at constant temperature); $kJ/m^2 \cdot mm$ (SI), $BTU/ft^2 \cdot in$ (USCS).

H_{rs} was assumed to be negligible because: (1) solar radiation is only effective for a few hours around noon in the winter months; (2) the snow pack has a high reflectivity; and (3) it was overcast 80 percent of the time. Subsequent calculations using predicted and observed data verified this assertion. Melt due to H_p is ignored since most of the precipitation during the test period was in the form of snow and the temperature of any rain was near 0°C. The internal energy change in the snow pack was also ignored, and model verification calculations indicate that this is justified.

Convection melt for a six-hour period is calculated as follows:

$$H_c = \begin{cases} K_{ca} V T & \text{(SI)} \quad (5a) \\ K_{cb} V(T - 32) & \text{(USCS)} \quad (5b) \end{cases}$$

Where H_c is calculated in kJ/m^2 (SI) or BTU/ft^2 (USCS); V is the wind speed in km/h (SI) or mi/h (USCS); T is the outside temperature in °C or °F; $K_{ca} = 14.64$; $K_{cb} = 1.153$. K_{c*} is based on the theoretical value developed by Light (Viessman et al, 1977). Condensation melt calculations for a six hour period are based upon the equations

$$H_e = \begin{cases} K_e V(e_a - e_i) & T > 0°C \quad (6) \\ K_i V(e_a - e_{si}) & T < 0°C \quad (7) \end{cases}$$

where e_a = atmospheric vapor pressure in pascals (SI) mb (USCS) e_i = vapor pressure over ice at 0°C; $K_e = 0.3052$ (SI); $K_e = 4.328$ (USCS); K_e is derived from Light's theoretical value (Viessman et al, 1977). e_{si} = saturated vapor pressure over ice for the given air temperature; $K_i = 0.0035$ (SI); $K_i = 0.499$ (USCS).

Long wave radiation (H_{rl}) was assumed to approximate black body radiation exchange between the average snow pack and the sky temperatures. On a clear night, the sky temperature was taken to be -40°C, otherwise it was taken to be the temperature at the base of the clouds which was assumed to be approximated by the dew point for the given atmospheric conditions. Mean snow pack temperatures were computed from the base and the outside air temperature. The base temperatures were assumed to be 0°C for the three heated bays and the ground. The snow-pack temperature for the overhang was taken to be the same as the air temperature. It was found that reducing the theoretical black body radiation by 50 percent gave the best fit. A downward adjustment was reasonable because: (1) both the snow and the sky depart from ideal black body behavior; (2) the sky radiation is a function of the cloud height, plus the degree and distribution of overcast; and (3) the snow pack also receives radiation from the surrounding trees which are warmer than the sky. Each of these factors would tend to reduce the actual radiation obtained from a theoretical analysis. For six hour theoretical radiation:

$$H_{rl} = K_r(T_{sk}^4 - T_{sn}^4) \quad (8)$$

where $K_r = 1.225 \times 10^{-6}$ (SI); $K_r = 1.028 \times 10^{-8}$ (USCS); T_{sk} = sky temperature K (SI), R (USCS); T_{sn} = snow pack temperature K, R. Conductive heat flux (H_f) was measured for the three heated bays. The heat flux through the overhang was considered to be zero. The ground heat flux was assumed to be 0.198 W/m^2 (0.623 $BTU/hr \cdot ft^2$). This assumption is consistent with U.S. Army Corps of Engineers data that the average melt due to heat flux through the ground is 0.508 mm/day (0.02 in/day) (Viessman et al, 1977). It should be noted that McCall is in an active geothermal area with a number of hot springs within 32 km radius of the test site; thus actual ground heat flux may exceed the assumed average value.

The resulting melt model becomes

$$H_m = H_{rl} + H_e + H_f + H_c \tag{9}$$

if $H_m > 0$ then:

$$M = \begin{cases} H_m/334.8 \text{ (SI)} & (10a) \\ H_m/748.8 \text{ (USCS)} & (10b) \end{cases}$$

where M is melt in millimeters (SI) or inches (USCS), H_m is kJ/m^2 (SI) or BTU/ft^2 (USCS). The water content for a given condition took the previous water content plus the precipitation for that period minus the possible melt. A summary of the parameters used in the model is found in Table 4.

Table 4

Summary of Model Parameters

Parameter \ Location	Bay 1	Bay 2	Bay 3	Overhang	Ground
Air Temperature	M_s	M_s	M_s	M_s	M_s
Dew Point	C_s	C_s	C_s	C_s	C_s
Vapor Pressure	C_s	C_s	C_s	C_s	C_s
Sky Temperature	C_s	C_s	C_s	C_s	C_s
Base Temp--°C (°F)	0 (32)	0 (32)	0 (32)	* (*)	0 (32)
Heat Flux--W/m^2 ($BTU/hr\cdot ft^2$)	M_d (M_d)	M_d (M_d)	M_d (M_d)	0 (0)	0.198† 0.623†

M_s = Measured and the same value for all conditions

C_s = Calculated from NOAA data and same for all conditions

M_d = Measured and different for all conditions

* = Same as outside air temperature

† = U.S. Army Corps of Engineers

<u>Model Verification</u>

Modeled water content data was compared to observed data under differing conditions to verify the assumptions in the model. The assumption that short wave radiation (H_{rs}) was small was born out by applying the model to the overhang with no radiation terms present. In this situation only convention (H_c) and condensation (H_e) terms were present. The predicted water content value fell within the observed mean values (i.e., 95 percent confidence interval, standard error of the mean) for four of the five cases (see Fig. 2). These findings confirm the assertion that ignoring short wave radiation does not seriously impair the model's ability to predict the observed values for the test period. The assumption that the heat flux (H_f) through the ground was approximately 0.198 W/m^2 (SI) [0.623 $BTU/hr\cdot ft^2$ (USCS)] was also confirmed since the predicted values were within the range of observed values (i.e., 95 percent confidence interval, standard error of the mean) for four of the five observations (see Fig. 2). Adjustment of the theoretical long wave radiation (H_{r1}) was used to match the predicted and measured values for the three heated bays. A value of 50 percent of the theoretical radiation gave the best fit for the observed data versus predicted values. In those cases where error occurred, the model was conservative by predicting a higher water content than was observed (Figs. 4 to 7).

Figure 4
WATER CONTENT: BAY 1 - GROUND

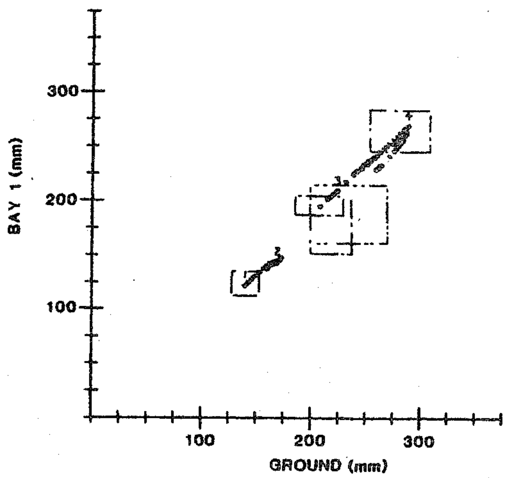


Figure 5
WATER CONTENT: BAY 2 - GROUND

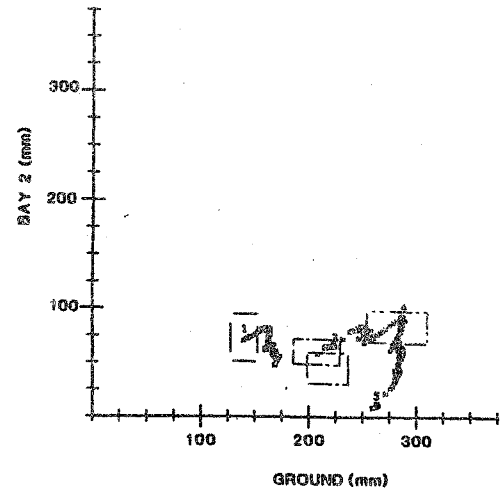


Figure 6
WATER CONTENT: BAY 3 - GROUND

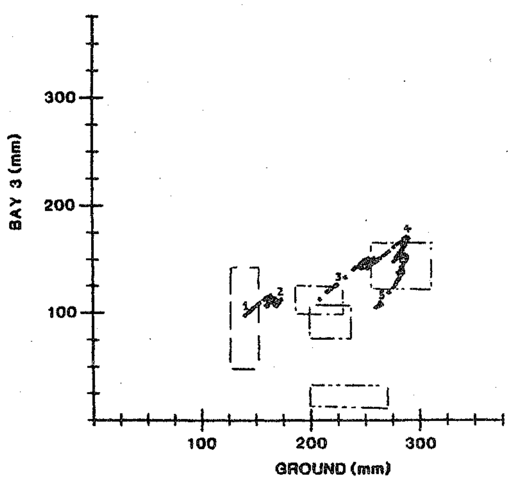
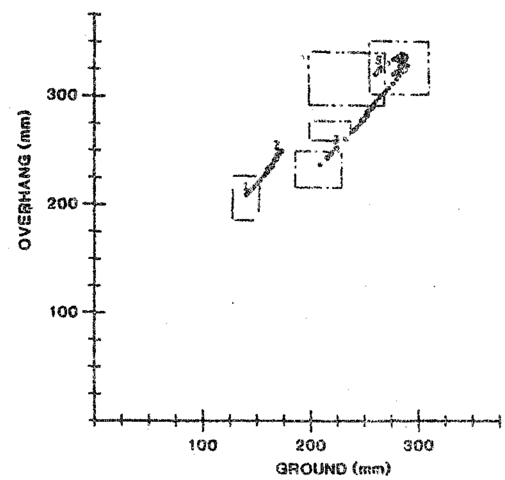


Figure 7
WATER CONTENT: OVERHANG - GROUND



Figs. 4-7 Boxes are ranges of observed values for 95% confidence interval std. err. of mn.

GROUND-TO-ROOF CONVERSION

The modeled water content data were plotted for the four thermal environments versus the ground water content to determine the ground-to-roof snow load ratio. Modeled data, starting with the observed data on Jan. 27, 1983, were used for computing the ground-to-roof conversion factors because these data accurately predicted observed ground snow load throughout the remainder of the test period. For each of the three bays and the overhang, the ground versus roof water contents (281 points per data set) were plotted with a HP-7225 X-Y plotter. A straight line was visually fit to the data where both the roof and the ground water contents were increasing. For each data set, the steepest slope of the line for ground vs. roof water contents on the plot was taken to be the critical slope for the heat flux condition (see Table 5). The critical angles corresponding to these slopes were then correlated with the average heat flux through the bay by linear regression ($r^2 = 0.906$; $n = 5$). The resulting equation was then slightly modified to be conservative by predicting a ground-to-roof conversion factor that was equal to or slightly greater than the observed values. This procedure gave the equation

$$C_{rg} = \begin{cases} \tan(48.7 - 8.68\,H_f)\,(\text{SI}) & (11a) \\ \tan(48.7 - 2.75\,H_f)\,(\text{USCS}) & (11b) \end{cases}$$

where C_{rg} is the roof snow load divided by the ground snow load; H_f heat flux through the roof in W/m^2 (SI), or $BTU/hr \cdot ft^2$ (USCS). For design purposes, a rigorous procedure

Table 5

Summary of Measured Ground Snow Load Conversion Parameters

Parameter \ Location	Bay 1	Bay 2	Bay 3	Overhang	Ground
Heat Flux--W/m^2 [$BTU/(hr \cdot ft^2)$]	0.476 (1.50)	1.49 (4.71)	0.903 (2.85)	0 (0)	0.197 (0.62)
Roof/Ground (slope) C_{rg}	0.900	0.727	0.810	1.19	1.00
Angle [arctan (C_{rg})]	42°	36°	39°	50°	45°
C_t*	1.29	1.04	1.16	1.70	-

*C_t [Eq. (1)] for the contiguous United States obtained by dividing Roof/ground by 0.7

should be used to compute the roof heat flux for known building thermal conditions. See for example McGuinness et al (1980).

DISCUSSION

This study indicates that the thermal mechanisms affecting roof snow loads are more complex than that which is implied by ANSI A58.1-1982. The standard predicts a value of C_t = 1.0 for bays 1 to 3 and C_t = 1.2 for the overhang. From Table 5 we observe that in all cases the measured values of C_t are greater than those predicted, and C_t is dependent upon heat flux. In light of these results it appears that a heated structure should be designed using C_t greater than 1.0, depending upon thermal conditions. Furthermore, it could be disasterous for a structure designed for a high heat flux to remain vacant and unheated for a snow season.

Ground-to-roof conversion factors predicted by this study are best suited for large snowfalls in regions of intermittent snowpacks. In this study we have demonstrated that the accumulation of snow on the ground and on the roof may be predicted with some degree of accuracy for a given snowfall. In regions where a permanent winter snowpack exists, a substantial amount of the roof snow may melt between snow storms. In these cases the standard ground-to-roof conversion factor could be considerably less than those predicted in this paper. Roof and ground snow depositions can be influenced by various regional climatic factors not included in this study. Ground snow pack may also be affected by soil characteristics that influence infiltration and runoff. Therefore, without additional data it would be tenuous to extend the findings of this research as summarized in Eq. (11) to general situations.

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