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FIELD TESTS OF A SURFACE ICE ACCRETION MEASUREMENT SYSTEM.(U)

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AIR FORCE GEOPHYSICS LABORATORY

HANSCOM AFB, MASSACHUSETTS 01731

AIR FORCE SYSTEMS COMMAND, USAF

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FOR THE COMMANDER

John Howard

Chief Scientist

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Rosemount ice detectors were installed at four New England locations to collect information on their response to icing near the earth's surface. Data were collected for 11 icing events during the 1979-80 winter season. These included, for each icing event, the recorded output of the ice detectors, the mass, thickness and physical properties of the ice on a control cylinder, and meteorological conditions pertinent to the field tests. The data were analyzed to determine how accurately ice amounts on the cylinder could be estimated from the output of the ice detectors. Results indicate that the detector

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would be excellent for objectively estimating icing amounts on a cylinder for in-cloud icing on mountaintops. A slight modification and further testing is necessary to best use the instrument to estimate icing amounts from freezing rain or drizzle. A method for making standardized observations of the mass and thickness of ice on cylinders with varying diameters is also presented.

Preface

I would like to thank Robert Skilling of the Blue Hill Observatory, John Govoni at the U.S. Army Cold Regions Research and Engineering Laboratory, and Chien-Hsiung Yang, Donald Grantham, and Stuart Muench at AFGL for their support during this program. I am also grateful to William Lamkin and Stuart Sheets for setting up and maintaining the ice detection equipment, and to Helen Connell for typing this report.

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1. BACKGROUND

An off-the-shelf ice detector manufactured by Rosemount Engineering Company, Minneapolis, Minnesota, was tested in a climatic chamber to determine its capability to measure ice accretion in a way that could be related to the accumulation of ice on stationary surface structures. The ice detector, Model 872 DC, is shown in Figure 1. It is one of several models that is used primarily to detect icing in the intake portion of turbo machinery such as aircraft engines. The sensor on the detector is cylinderical (2.7 cm long and 0.6 cm in diameter) with a hemispheric top. It oscillates ultrasonically, and as ice builds up on it, the frequency of oscillation shifts. When the ice reaches a preset amount, an internal heater melts the ice off the sensor and the adjacent part of the detector. In about 7 sec the unit is ready to sense subsequent icing. The climatic chamber tests indicated a high linear correlation between the number of detector deicing cycles and the mass and thickness of ice manually measured on cylinders. A detailed description of the instrument, the test conditions, an overview on the dynamics of icing, and an analysis of the test results has been published in a previous AFGL report.[1]

(Received for publication 19 December 1980)

1. Tattelman, P. (19[illegible]) Climatic Chamber Tests of a Surface Ice Accretion Measurement System, AFGL-TR-[illegible], AD A07[illegible].

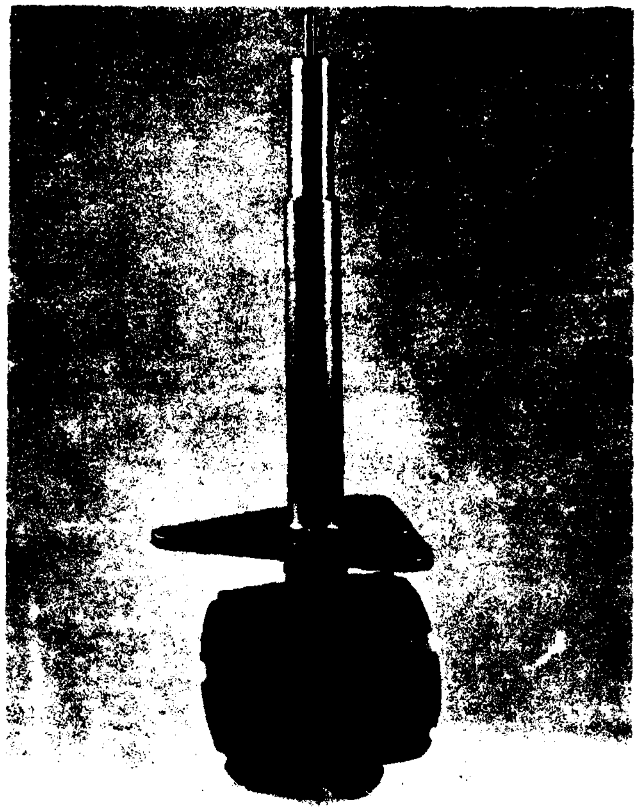

Figure 1. The Rosemount Model 872DC Ice Detector. The sensing probe sits atop the 25.4-cm (10-in.) strut. During deicing, the sensor and the top 7.6 cm (3-in.) of the strut are heated

Subsequent to the positive results of the climatic chamber tests, it was decided to observe the ice detector in the more turbulent and variable natural environment. Our goal was to determine if the relationships between instrument output and the mass and thickness of ice on cylinders could be used to develop a method of objectively estimating ice accretion amounts. Observations of icing amounts would be useful for many applications—anticipating transportation disruptions or power and communication outages. The U.S. Air Force is most concerned about accurate icing design criteria for susceptible surface structures such as communications towers and radomes which are prone to destruction under a heavy load of ice. For example, an Air Force communications tower atop a mountain in Italy was severely damaged in March 1979 due to a much larger ice accumulation than the amount estimated for the preconstruction design criteria. Although overly conservative design estimates would enhance survivability, they would greatly increase construction costs. Accurate icing information would also enable designers to locate structures in nearby less susceptible locations or plan for backup equipment in heavy icing areas.

In order to improve the accuracy of icing design values, it will be necessary to collect standardized icing observations at a representative number of sites where conventional weather observations are also available. Data collected could be used to develop models relating icing rates to synoptic conditions. Ice amounts could then be inferred for locations where there is knowledge of the frequency of conditions that produce icing. Ultimately, the collection of actual icing observations could be used to make more refined estimates of ice amounts.

2. THE WINTER FIELD TESTS

Rosemount Model 872DC ice detectors were mounted on a stand and installed at the following four New England sites:

(a) Loon Mountain Summit, Lincoln, New Hampshire (elevation 915 m)

(b) Westford, Massachusetts (elevation 64 m)

(c) Hanscom AFB, Massachusetts (elevation 70 m)

(d) Blue Hill Observatory, Milton, Massachusetts (elevation 190 m)

These locations are shown graphically in Figure 2.

2.1 Equipment

A cylinder 2.5 cm (1-in.) in diameter and 30.5 cm (12-in.) in length, was mounted on a wind vane colocated on the stand with the ice detector. This arrangement can be seen in Figure 3 that shows the installation at Westford. The cylinder is kept normal to the wind flow by the vane to standardize thickness measurement; it can be removed to determine the mass of the ice. The distance between the vane and the ice detector is approximately 1 meter.

The ice detector works in conjunction with a Model 524H controller, located indoors, that regulates the heating cycles and output signals. Details of the operation can be found in the Rosemount instruction manual.[2] In addition to the ice detection system, equipment at each site included a 2-channel recorder, a digital counter, a vernier caliper, and a triple-beam balance. The recorder was used to collect the discrete output (that is, to indicate each heating cycle) on one channel and the analog voltage that shows the change in voltage as ice builds up on the sensor on the other channel. The counter simply registered the total number of heating cycles and the vernier caliper was used to measure the dimensions of the ice on the cylinder. The mass of ice on the cylinder was determined on the beam balance after placing the cylinder and ice in a plastic bag.

2. Rosemount, Inc. (1975) Instruction Manual 57522C, Rosemount, Inc., P.O. Box 35129, Minneapolis, Minnesota 55435.

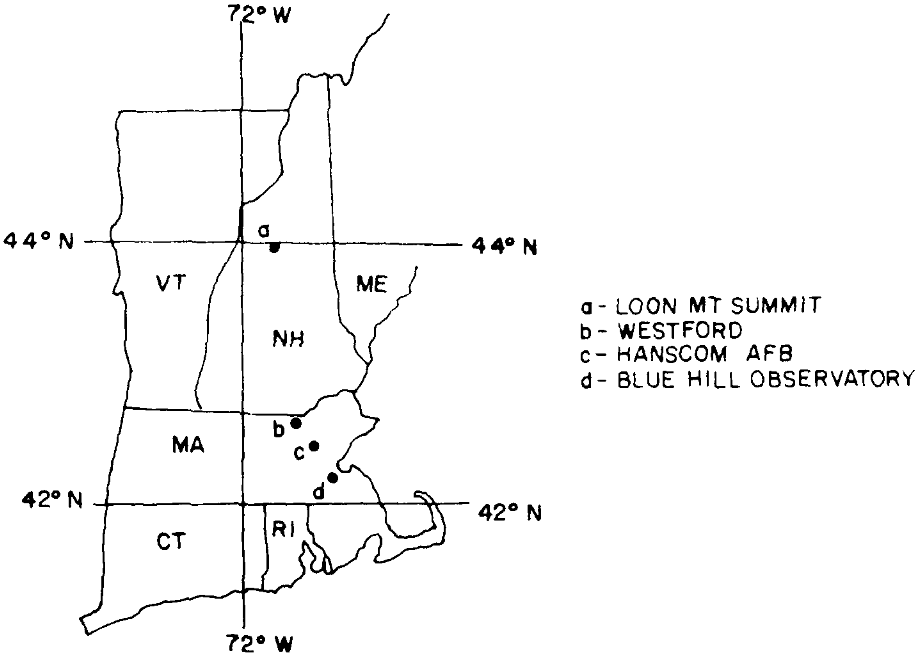

Figure 2. Location of Field Test Sites

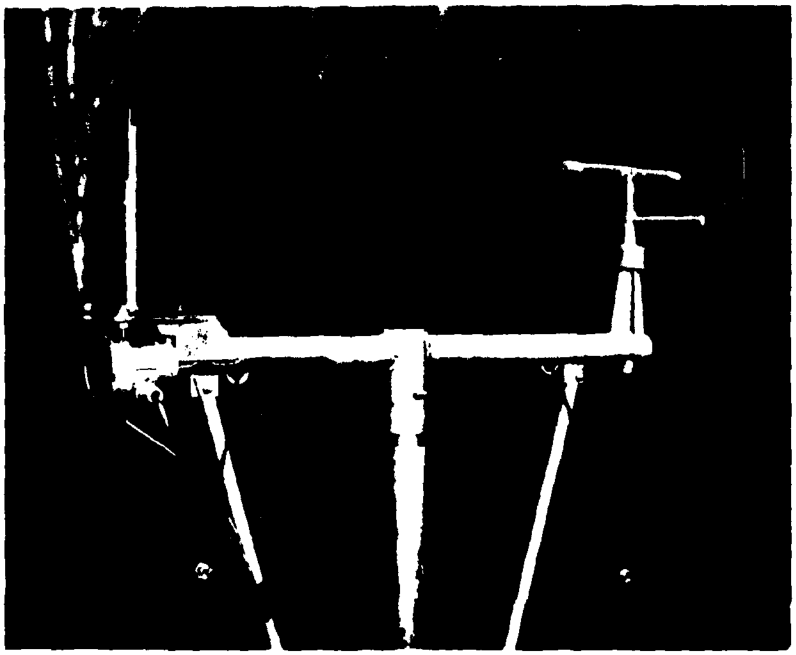

Figure 3. The Ice Detector Installation at Westford, Massachusetts

2.2 Data Collection

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Table 1. Summary of Icing Events, Associated Weather, Ice Measurements, [illegible]. M_C, M_P, and T'_C, T'_P are estimates of the mass and thickness, respectively, [illegible] previous climatic chamber tests

[illegible]

Our previous report on the Rosemount ice detector described 42 1-hr climatic chamber tests using the Model 872DC ice detection system. One-half were with freezing rain, the other-half with in-cloud icing. After each 1-hr test, the mass of the ice, MRIT, and VIT were determined for the 2.5-cm diam cylinder (in addition to other cylinder sizes). The number of deicing cycles was also recorded for three ice detectors. Two of the ice detectors were Model 872DC. The third, Model 871FA, differs only in the length and configuration of the strut. The least-squares linear regression information for the mass of ice on the cylinder versus the number of cycles for each detector is given in Table 2. The regression lines for the freezing rain and in-cloud icing data in Table 2 are shown in Figure 4. The marked improvement in the regression information by separating the freezing rain and in-cloud icing tests indicates that the ice detector responds differently to the two types of icing. This is discussed in the report on the chamber tests.[1]

Table 2. Linear Least-Squares Regression Information for the Mass of Ice on the 25-mm Diam Cylinder vs the Number of Instrument Cycles for Each Detector, and for All Detectors Combined Based on the Climatic Chamber Tests. (Results are given for all conditions together and for the freezing rain and in-cloud icing conditions separately)

Conditions	Detector Number Model	Number of Test Points	Slope	Y Intercept	Correlation (r)	SEE (grams)
All	1/872DC	42	3.44	10.29	0.80	29.2
All	2/871FA	41	3.66	7.42	0.80	29.6
All	3/872DC	42	4.32	8.94	0.79	29.8
In-cloud icing	1/872DC	21	1.89	9.52	0.92	8.9
In-cloud icing	2/871FA	20	1.94	8.12	0.93	8.3
In-cloud icing	3/872DC	21	2.38	8.99	0.94	7.9
In-cloud icing	All	62	2.01	9.35	0.92	9.0
Freezing rain	1/872DC	21	5.33	11.43	0.99	9.4
Freezing rain	2/871FA	21	5.75	5.11	0.99	9.9
Freezing rain	3/872DC	21	6.97	6.61	0.98	11.9
Freezing rain	All	63	5.82	9.10	0.98	13.3

Two of the four Model 872DC ice detectors used in the climatic chamber tests were also used in the field tests at Hanscom (detector 1) and Loon Mt. (detector 3). To smooth out the differences in the response of the individual detectors, it was decided to pool the data for all three detectors to develop linear least-squares regression lines of the number of deicing cycles vs the mass of ice on a 2.5-cm diam cylinder per 30.5 cm length. The resulting equations are:

$$\hat{M}_r = 9.1 + 5.3N \, , \qquad (1)$$

and

$$\hat{M}_c = 9.4 + 2.0N \, , \qquad (2)$$

where $\hat{M}_r$ and $\hat{M}_c$ are estimates of the mass of ice for freezing rain (subscript r), and in-cloud icing (subscript c), and N is the number of detector deicing cycles. The correlation and standard error of estimate (SEE) are given in Table 3.

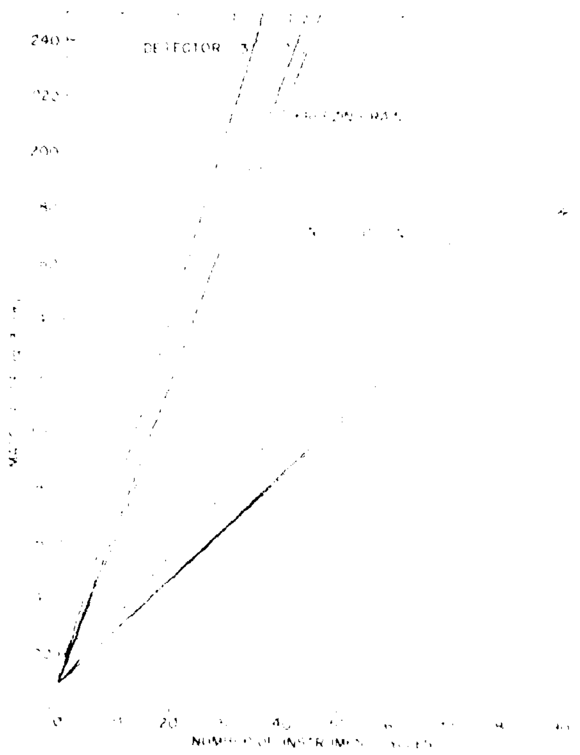

Figure 4. Least-squares Linear Regression Lines for the Mass of Ice on the 2.5-cm Dia Cylinder vs the Number of Detector Deicing Cycles From Information in Table 2 for Freezing Rain and In-cloud Icing

The estimates for ice thickness in Table 1 were based on a radial ice thickness concept presented in the climatic chamber test report.[1] This implies that icing will produce a uniform coating on a cylinder, so that the thickness of ice is the radius of the cylinder *and* ice minus the radius of the cylinder. From simple geometry, the theoretical radial ice thickness, T, can be calculated using the expression

$$T = \left(\frac{M_I}{\rho_I \pi L} + r^2 \right)^{1/2} - r \tag{3}$$

where M_I is the mass of ice on the cylinder, ρ_I is the ice density, L is the length of the cylinder, and r its radius. For a 2.54-cm diam cylinder with a length of 30.48 cm (1 ft) and using an ice density 0.8 g cm^{-3} for ice formed by freezing rain, Eq. (3) becomes

$$\hat{T}_r = \left(\frac{M_I}{76.6} + 1.61 \right)^{1/2} - 1.27 \tag{4}$$

where the estimated radial ice thickness for freezing rain, $\hat{T}_r$ is in cm, and M_I is in grams per 30.5 cm cylinder length. For in-cloud icing, an ice density of 0.6 g cm^{-3} is used in Eq. (3) so that

$$\hat{T}_c = \left(\frac{M_I}{57.45} + 1.61 \right)^{1/2} - 1.27 \tag{5}$$

where $\hat{T}_c$ is the estimated radial ice thickness for in-cloud icing. The derivation of Eq. (3) and the rationale for the choice of values for ice density is discussed in detail in Section 6 of the climatic chamber test report.[1]

The thickness of ice on a structure is necessary for the engineer to calculate the increased surface area that will be exposed to wind loading. During natural ice accretion, ice thickness varies and assumes a variety of shapes depending on the orientation and size of the collecting surface and the synoptic conditions. Also, ice may remain on a structure for some time after a storm and subsequent strong winds may be from a different direction. Although radial ice thickness does not describe the shape of accreted ice occurring under natural conditions, it is a reasonable compromise for calculating increased surface area, for all possible orientations to the wind, of a rigid ice coated structure.

In Table 1, the estimated values for the ice thickness are represented by $\hat{T}'_c$ and $\hat{T}'_r$, where

$$\hat{T}'_c = 2\,\hat{T}_c\,, \tag{6}$$

and

$$\hat{T}'_r = 2\,\hat{T}_r . \tag{7}$$

This is for comparison with MRIT and VIT, since the actual increase in the thickness of the cylinder plus ice is twice the radial ice thickness. A good estimate of the thickness would fall between the MRIT and the VIT.

The information on the type of weather in Table 1 shows that, frequently, a variety of conditions combine to produce icing. Therefore, for each icing event, estimates were made of the mass and thickness of ice for both freezing rain and in-cloud icing. These two types of icing represent the upper and lower limits of drop sizes that produce natural icing. The difference in drop size distribution is the reason for the different regression lines for freezing rain and in-cloud icing in Figure 4. The mean droplet diameter for the freezing rain icing tests was about 800 μm; for the in-cloud icing tests it was about 35 μm. Freezing drizzle, which was the most common weather type for the icing events, has droplet diameters between 200 and 500 μm.[3,4] The optimum result would be to have the measured mass of ice on the cylinder, for the mixed icing or freezing drizzle icing events fall somewhere between the freezing rain and in-cloud icing measurements.

3.2 Analysis

Table 1 provides information on 14 icing events. Unfortunately, it was a dry winter at Loon Mt. and little data were collected there. Since access to the summit was limited, the two events that are listed have missing data, and for the 14 January event, the record of the number of instrument cycles was lost so it is not certain that the reported number of detector cycles is only for that event. Therefore, the Loon Mt. data are not considered in any further analyses. For the 18 January event at Westford, the ice accumulation was not sufficient to produce any detector cycles. Figure 5 shows the regression lines for $\hat{M}_r$ and $\hat{M}_c$; also shown are circled points for the measured mass of ice on the cylinder for the remaining 11 icing events. Each point is identified by the event number in Table 1.

Six of the eleven points in Figure 5 fall between the regression lines. Two of the five events not within the regression lines (numbers 1 and 2) were the result of wet snow. Two other events, numbers 3 and 9, had some snow mixed in. Although the ice detector response to wet snow is not known, this small sample indicates that the mass build-up of ice on the cylinder per instrument cycle may be less than that

3. Mason, B.J. (1971) The Physics of Clouds, 2nd ed., Oxford University Press, London, England.

4. Huschke, R.E., Ed. (1971) Glossary of Meteorology, 2nd printing, American Meteorological Society, Boston, Massachusetts

for in-cloud icing. Although an effort was made to measure icing amounts at the conclusion of an event, it was not always possible to tell if icing had ceased, and on some occasions the observer could not be present at the conclusion of icing. The elapsed time between the end of icing until the icing amounts on the cylinder were observed is given in Table 1. It can be seen that events 3, 8, and 9 were the only instances where more than 1 hr elapsed before the observation was made. Even though temperatures remained at or below freezing during this period, some loss of ice on the cylinder, due to melting or evaporation, was likely. Therefore, all of the points below the in-cloud icing regression line in Figure 5 represent icing events which either involved snow and/or a substantial period before observation allowing for ice loss.

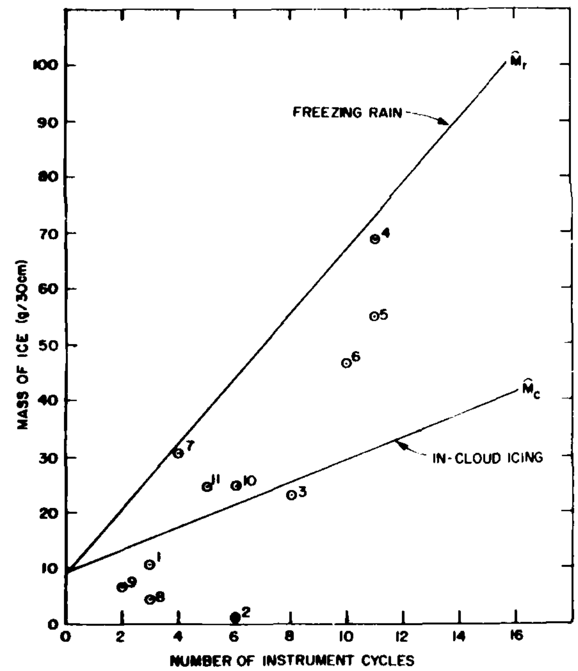

Figure 5. Regression Lines for the Mass of Ice Measured on the 2.5-cm Diam Cylinder vs the Number of Instrument Cycles for Freezing Rain [Eq. (1)], and for In-cloud Icing [Eq. (2)] Based on the Climatic Chamber Tests. Circled points represent the mass of ice measured on the cylinder vs the number of cycles for the field test icing events. Event numbers from Table 1 identify each point

The icing events included some other interesting aspects. For instance, icicles did not form during any of the events. Also, the two heaviest icing periods (events 4 and 5) occurred with only 0.8 mm (0.03 in.) and 0.5 mm (0.02 in.) of melted precipitation, respectively. Both events were part of a static synoptic situation with drizzle, separated by a period of time with no precipitation. Unfortunately, no in-cloud icing occurred; except at Blue Hill (events 1 and 2) when the bulk of resulting ice was caused by wet snow which formed a slush that froze.

To get an appreciation of our method for determining the ice thickness, Figure 6 shows the ice thickness curves from Eqs. (6) and (7) along with the plotted values of the actual mass of ice vs the average of the VIT and the MRIT for each icing event. These results indicate that the radial ice thickness approach will provide reasonable estimates of ice thickness based on the mass of ice.

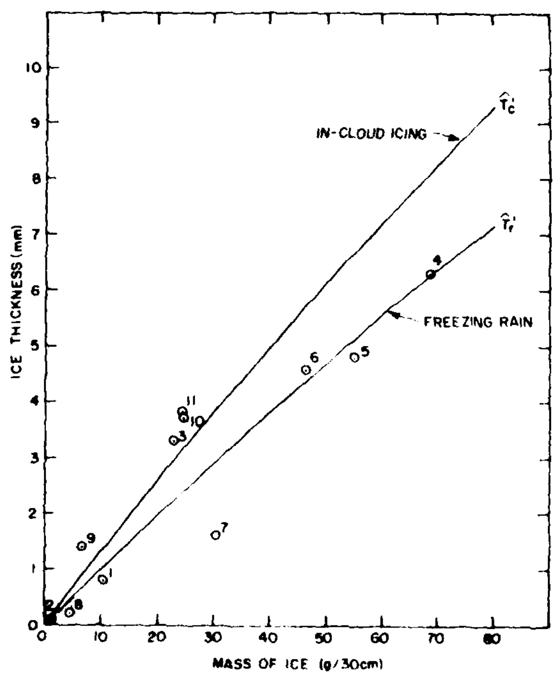

Figure 6. Radial Ice Thickness Curves for In-cloud Icing [from Eq. (6)], and for Freezing Rain [from Eq. (7)] vs the Mass of Ice on the 2.5-cm Diam Cylinder. Circled points represent the average of the MRIT and the VIT vs the actual mass of ice measured on the cylinder for each icing event. Event numbers from Table 1 identify each point

Examination of the information in Table 1 and Figure 5 leads one to support the potential of the Rosemount 872DC ice detection system as a network instrument for making objective observations of ice accretion. Additional data need to be collected, perhaps in a climatic chamber, to establish regression lines, for freezing drizzle or mixed icing, that would fall between those for freezing rain and in-cloud icing.

3.3 Equipment Problems

The optimism expressed in the preceding section is tempered by two problems; water retention on the flat surface between the ice detector strut and the sensor, and instrument calibration. The problem of water retention on the strut was originally noted at the time of the chamber tests.[1] During the heating cycle, melt water from the sensor flows down to the flat surface of the top of the strut. Surface tension keeps the liquid in place and it freezes. With subsequent deicing cycles, the melt water can eventually surround the sensor in a puddle deep enough to automatically trip the deice mode even though the actual icing may have stopped. This occurred during prolonged icing tests with winds less than about 15 knots. When the wind was stronger, the melt water was blown off. It was not a problem during the in-cloud icing tests that had winds of at least 15 knots.

Excessive instrument cycling due to freezing melt-water occurred during two of the field test icing events, numbers 5 and 11. These were corrected to the number of cycles shown in Table 1, by analyzing the recorded analog output for the distinctive shape of the erroneous cycle. It was found that this response could be artificially duplicated by spraying the sensor with an atomizer through several deicing cycles until the melt water reached the critical depth. At that point, the instrument would cycle automatically every time the puddle froze. Tilting the detector did not facilitate the flow of water from the top of the strut until its angle from the vertical was more than 60°. Positioning the strut at this angle was not a viable solution since the instrument response would become a function of wind direction. The most practical way to eliminate this problem would be to taper the top of the strut to facilitate drainage. Representatives at Rosemount felt that this could be accomplished—but with additional cost.

The four 872DC ice detectors were returned to Rosemount for evaluation at the conclusion of the winter field tests. When purchased in March 1977, the ice detectors were calibrated at the factory to deice (reach the trip point) when 0.51 mm (0.02 in.) of ice accumulated on the sensor. Rosemount found that two of the detectors, those used at Westford and Loon Mt., were only slightly out of calibration with a trip point of 0.53 mm. The Hanscom and Blue Hill detectors, however, were substantially out of calibration with trip points of 0.44 mm and 0.39 mm respectively. Rosemount was unable to determine the cause, but noted that the sensors on these two detectors were discolored. They felt that this was probably caused by overheating that caused a material stress that affected the calibration. The discoloration was not present at the conclusion of the climatic chamber tests but it did become apparent at the beginning of the field tests. It might have been caused by an extended period with the heater 'on' while testing the initial installation in the field. The obvious change in color would at least signal the need for recalibration if this happened during actual use of the detector for icing observations.

The change in calibration was less than 5% for the Westford and Loon Mt. detectors. For the Blue Hill and Hanscom detectors, the respective changes in calibration of 24% and 14% were reason enough to reexamine the results in Table 1 and Figure 5. The number of cycles at Blue Hill and Hanscom in Table 1 were decreased by 24% and 14% respectively, to the nearest tenth of a cycle, and all the icing events were replotted in Figure 7. The number of cycles for event No. 7 was not adjusted because the detectors at Hanscom and Loon Mt. were switched after that icing event, but prior to the collection of additional data, to aid in correcting a minor wiring problem. The adjusted values presented in Figure 7 do not affect the generally positive results of the field tests presented previously.

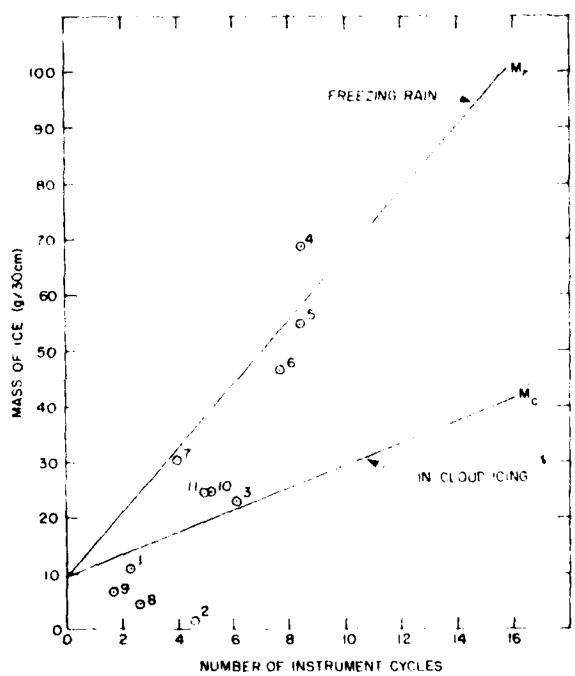

Figure 7. Regression Lines for the Mass of Ice Measured on the 2.5-cm Diam Cylinder vs the Number of Instrument Cycles for Freezing Rain [Eq. (1)], and for In-cloud Icing [Eq. (2)] Based on the Climatic Chamber Tests. Circled points represent the mass of ice measured on the cylinder vs the number of cycles adjusted to compensate for instrument error. Event numbers from Table 1 identify each point

4. CONCLUSIONS

A limited amount of surface icing data was collected. At the four sites there were eleven icing events for which usable data were obtained. Regression equations for estimating the mass of ice on a 2.5-cm diam, 30.5-cm long cylinder from the number of detector deicing cycles were previously developed, from climatic chamber test data, for freezing rain, and in-cloud icing. These conditions represent the upper and lower limits of drop sizes that produce icing. Most of the icing events in the field were a mixture of precipitation types which produced a measured mass of ice on the cylinder between those estimated by the two regression equations. The measured mass of ice was subjectively considered to be substantially below the estimated amount in only three events; Nos. 2, 8, and 9 (see Table 1 and Figure 7). However, event No. 2 was the result of wet snow, and ice measurements on the cylinder for events 8 and 9 were delayed for a substantial period after the end of icing, increasing the likelihood that some ice was lost, and degrading the comparison with the estimated mass.

Unfortunately, no data were collected for in-cloud icing, a phenomenon that is most frequent at high altitude locations exposed to the passage of supercooled cloud droplets. This type of icing has become a critical contemporary design problem due to the proliferation of line-of-sight communications towers that are being located on mountain tops. Our subjective opinion is that the Rosemount 872DC ice detection system would provide good observations of in-cloud icing amounts at such locations. This opinion is based on the regression information for the mass of ice vs the number of cycles from the climatic chamber tests for in-cloud icing, and the positive indication that the regression lines for the mass of ice for both freezing rain and in-cloud icing delineate the mass of ice measured for the field test icing events.

The major hindrance to utilization of the detector "off-the-shelf" for making icing observations is the problem of retention of melt water on the flat surface area on top of the strut on which the sensor is located. This retained water can cause erroneous cycling upon refreezing. This situation occurs during light winds ($<$ 15 knots). Since stronger winds blow the melt water off, it is not a problem during in-cloud icing which requires fairly strong winds to blow supercooled droplets past a stationary surface to form ice. The problem could be eliminated by tapering the top of the strut to facilitate drainage.

5. RECOMMENDATIONS FOR FUTURE EFFORTS

The Rosemount Model 872DC ice detection system has strong potential as a network instrument for objectively monitoring ice accretion amounts that can be related to the mass and thickness of ice on a cylinder. To achieve this goal for all types of icing, it will be necessary to modify the Model 872 detector (that is, taper the top of the strut) to facilitate drainage of melt water. An estimate for the cost of modification has been provided by Rosemount. It will also be necessary to conduct further testing, either in the climatic chamber or in the field, to establish regression lines (for instrument output vs mass of accumulated ice on a standard cylinder size) for freezing drizzle and mixed icing. This effort would require 2 to 3 years, followed by additional data collection at sites where conventional observations are available.

Another option would be to utilize the four model 872DC ice detectors to collect data on in-cloud icing. Modification would not be necessary because in-cloud icing occurs most frequently with strong winds (> 15 knots), which are necessary to carry supercooled cloud droplets across a stationary structure. This would blow melt water from the detector. In-cloud icing, frequently referred to as rime icing, is an important consideration in the design and construction of communications towers which are currently being placed on mountain tops. Our knowledge of this phenomenon would be greatly enhanced if observations of ice amounts were made in conjunction with conventional observations at mountain top locations. We have learned at Loon Mt. that, until enough experience has been gained utilizing the Rosemount ice detector, such a remote site should be monitored 24 hrs a day to insure the best quality data. A 2- to 3-year data collection program would enable more refined estimates of rime icing amounts at other mountain top locations.