RESOLVING AMBIGUITIES IN INTERPRETING THE THERMAL SIGNATURE OF ICE AND WATER IN AERIAL THERMOGRAMS OF FLAT ROOFS

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A Project Conducted for the

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INDEX PAGE

1. INTRODUCTION

The application of aerial thermography to the study of heat loss from flat-roofed buildings has been under investigation both in Canada and the United States for the past several years. In March 1977 the Department of Energy, Mines, and Resources (EMR) undertook an energy conservation project which included a survey by aerial thermography of all industrial, commercial, and institutional sites in the major cities in Prince Edward Island and Nova Scotia. EMR sponsored a survey-in-depth of 16 sites in Prince Edward Island as a sample set to study and reveal problems likely to be associated with the use of aerial thermograms to detect heat loss. The results of this study are contained in a report entitled "An Assessment of the Application of Aerial Thermography to the Measurement of Heat Loss on Flat-Roofed Buildings and Buried Heating Lines".

At the completion of the study it was concluded that aerial thermograms could be used to detect damaged insulation, poorly insulated buildings, and buried heating lines. It was also found that the thermogram of a roof with patches of water or ice could not be interpreted because the basic temperature map of such a roof - a prerequisite to a heat-loss analysis - could not be determined. The correct temperature distribution, although not necessarily a sufficient one, is a necessary condition for a valid heat-loss analysis. In the 1977 report this difficulty is expressed as a problem that

> "reduces to quantitatively interpreting changes of contrast on a surface when that contrast is, or may be, modified by more than one factor at the same time.
>
> In the present study, the problem was perceived as arising from three unknown factors, none of which were readily relatable to the other two and the sum total of which left the interpreter with an inconclusive result which the team making the follow-up visit could not sort out except by inference:
>
> 1. The size of a wet area on a roof when the thermography was taken, the depth of water, and the presence and size of any surrounding damp area could not be established with certainty.
>
> 2. Nothing in the data could be used as a basis for establishing whether the surface water was 100% in the liquid phase, or partially frozen, or completely frozen when the thermography was taken.
>
> 3. The exact allowance to be made for the higher apparent temperatures of water and

ice surfaces due to the higher emissivity of these surfaces, but as modified by the effective sky temperature at the time, was not known because an effective sky temperature was not recorded in the data set."

The report goes on to say that

"Factor (2) posed a particular dilemna for the interpreters in the present project because one of the "warmer" regions had apparent temperatures close to $0^{o}C$. In assessing the thermogram of a wet roof for possible excessive heat loss, it is critically important to know whether the surface in question was covered entirely by water or by ice when the thermogram was taken. If it was, the water or the ice would presumably be in thermal equilibrum with the roof surface and the ambient air. If it were not, i.e. water and ice were both present, the water and ice would presumably be at equilibrium with each other at $0^{o}C$ regardless of the "true" roof temperature."

and that

"The conclusion to be drawn from the experience gained on the project in dealing with "warm" areas in the thermal signatures of wet roofs is that a reliable interpretation as to the existence of excessive heat loss should not be attempted unless the contrast above background is very marked i.e. in the order of several degrees. Furthermore, in the case of a surface exhibiting an apparent temperature near the freezing point of water some independent means must be found for establishing that the water was in a single phase before any reliance can be placed on an interpretation of the higher temperature as being due to excessive heat loss."

In assessing the results of the 1977 project the report states that

"To assess heat loss from roofs that do not meet the criterion for dryness when the aerial thermography is taken will be moderately successful at best and will be very time-consuming. When wet roofs cannot be avoided, a well-documented control test-site appears to be a necessity. In general, it is felt that the use of the technique in this particular set of circumstances is pushing the state-of-the-art, as far as the knowledge available to an interpreter to confirm an analysis is concerned."

Finally, the 1977 report recommended that

"for at least two of the flight lines in Charlottetown, a second set of remotely-sensed data be collected under dry-roof conditions and the data from the new set and the present set be analysed together as supplementary confirmation of the interpretation of excess heat loss from roofs that were water or ice-covered at the time the thermography was taken for the present study."

The work described in the present report is an experiment aimed first at finding solutions to factors 2 and 3 of the general problem quoted above and second, at repeating some of the remote-sensing flights when the roofs were drier. Basically, a procedure was being sought in the experiment that a) would ease the task of establishing a correct temperature map over a roof and b) if successful would be practical from the point of view of being easily repeated in other thermography projects. When the correct temperature map had been obtained, its impact on the interpretation phase could be assessed.

In the experiment as originally proposed, part of a roof was to be covered with a controlled water surface. The surface temperature of this water and the surface temperature of the surrounding dry roof were to be measured at the time the airborne data was taken. Following a suggestion from the Canda Centre for Remote Sensing, it was further agreed that a portion of the same roof, presumed to be dry initially, should be sprayed directly with water and allowed to stabilize thermally before the airborne data was collected. Its temperature was to be measured also when the airborne data was taken. The airborne data would then be examined in the light of the measurements of the temperatures of the controlled water surface, the sprayed surface, and the dry surface to determine the correct increment in apparent radiation temperature between a dry surface and a wet or frozen surface at the same temperature. With this information the correct temperature distribution on a roof could be determined. (Note 1)

In the following three sections of this report we describe how the data for the experiment was acquired, how it was analysed, and how the resulting information was used to derive temperature distributions on roofs. In addition to the work on the control surface, thermograms for a number of other buildings were examined, and the findings compared with the analyses done on the same roofs in 1977 when surface conditions were wetter. The results of this comparative analysis are presented in a separate section. The final sections of the report present the conclusions drawn from the study and the recommendations.

Note 1: In this report we shall define three temperatures for a surface: T, T_B, and T_A. T is the actual physical temperature of the surface as measured by a thermometer or a thermocouple, T_B and T_A are radiant temperatures which relate to the radiant flux given off by the surface. T_B, the brightness temperature, is the radiant temperature of the surface as measured by an ideal radiometer calibrated against a perfect black body. In relation to T, T_B will be sensitive to the emissivity of the surface and will include the contribution of radiation from other sources as it is reflected or scattered into the ideal radiometer. T_A, the apparent radiant temperature of the surface, is the temperature indicated by a real radiometer operating in a real environment. It thus includes any biasses in the radiometer or the signal-processing equipment used to convert the readings taken from it to a useable form and any effects of atmosphere attenuation on the received signal.

2 DETAILS OF THE PROJECT

2.1 Scope

The project encompassed two principal activities. First, a set of contact and radiant temperature measurements were made on wet and dry parts of a roof in Charlottetown, P.E.I. and the results related to airborne thermal infrared signatures taken at the same time. The objective of this activity was to test a procedure for deriving a true temperature map over dry, wet, and frozen regions of a roof. Suitable allowances must be made for changes in contrast at dry, wet or frozen areas on a roof to take account of a) the difference in emissivity of dry gravel and water or ice and b) the effect of reflected sky radiation at these surfaces.

Second, aerial thermographs taken at the same time for a number of other sites in Charlottetown were analysed for heat loss and the results compared to heat loss analyses done for the same sites in 1977. The objective of this activity was to assess how much heat-loss analysis of roofs with wet patches would be improved if the correct temperature was known over the entire surface.

2.2 Professional Support in Charlottetown

Contractual arrangements were made for the services of Professor D. Gillis, Head of Engineering at the Univeristy of Prince Edward Island. Mr. Gillis was selected by the P.E.I. government to implement the infrared heat-loss part of a broad energy conservation program in the province and since 1977 has built up a unique background of practical experience in interpretation of thermograms, ground-truth verification of analyses, and presentation and discussion of results to building owners. Mr. Gillis also directed the preparation of the control site.

2.3 Specifications for the Data

The conditions under which the data for the project was acquired are specified as follows:

2.3.1 Ground Truth

(i) A 16x16-metre square grid of 81 points was laid out on a large roof of conventional construction. The roof selected was free of any known, serious heat-loss anomalies and was reasonably isolated, especially with regard to radiant coupling to the walls of nearby buildings.

(ii) On the same roof, a rectangular pool of water a few centimetres deep was set up and allowed to stabilize to the ambient air temperature . Rock salt was added to the water to keep it from freezing.

(iii) The actual and radiant temperature of the two control surfaces in (i) and (ii) were measured with precision thermocouples and a portable infrared radiometer. The temperatures of the control grid in (i) were measured twice during the night of the experiment, once while it was completely dry and again after half of it had been sprayed with water and allowed to stabilize. The second measurement coincided with the remote sensing flight.

(iv) The control roof and the majority of other flat roofs in Charlottetown were essentially free of snow and dry. Only isolated patches of snow or water were present. Below-freezing temperatures, a lightly overcast sky and light winds were present.

2.3.2 Airborne Data

(i) Infrared thermography in the 8-14 micron band was collected at an altitude of 550 metres with the CCRS Daedalus line scanner.

(ii) Daytime colour photography on 23x23 cm Kodak 2445 negative colour film was collected with 60% overlap along the flight line to allow stereo viewing. The camera was fitted with a 152 mm lens. Thermal infrared data was collected simultaneously with the daytime photography also at 550 metres.

(iii) 30% sidelap was specified for the infrared and the photographic data.

2.4 Schedule of Activities

The 81-point control grid was laid out and the thermocouples installed on the roof of the Holland College Royalty Centre during the week of March 19,1978. This site is near the northwest limits of the city and is clear of any near-by tall buildings. The flight crew was alerted on Saturday, March 25 that conditions were improving rapidly and would continue to improve for another 1-1/2 days before bad weather moved in. The decision to proceed was taken the following morning, March 26, and the aircraft and sensors were prepared immediately. The daytime flights were done as soon as the aircraft arrived at Charlottetown - between 3:00 and 4:00 P.M. local time - to take advantage of the remaining sunlight.

The rectangular pool was set up at 6:00 P.M., March 26. Filling began at 7:00 P.M. and continued until about 9:30 P.M.

The first temperature measurement on the control grid was made between 8:30 P.M. and 9:00 P.M.; one-half of the grid was sprayed immediately after. The spraying took approximately 30 minutes, ending at 9:30 P.M.. The first measurement of the temperature of the pool's surface was taken at 10:30 P.M.

The remote sensing flights over Charlottetown took place between 11:00 P.M. and 11:30 P.M., with the data for the control site being taken at 11:10 P.M..

The second set of in-situ temperature measurements on the two control surfaces began at 11:15 P.M., immediately after the aircraft has passed overhead.

The analysis of the data and visits to the sites were made between April 26 and May 11.

3. DATA ACQUISITION

3.1 Preparation of the Control Site

The roof of the main building of the Holland College Royalty Centre campus was selected as a control roof because the building is readily accessible during quiet hours, there is a supervisor on duty 24 hours a day and there are no other tall buidings nearby. The building has two stories and a heated glass penthouse suitable for working in. The roof is of conventional design with a surface layer of tar and gravel. The gravel covers the tar completely, being about 1.5 cms. depth of 1 cm. size crushed stone.

The 81-point grid and the rectangular pool of water were situated on the roof of the building as shown in Figure 3.1. Figure 3.2 is a sketch of the interior floor plan of the building relating its position to the position of the control grid. The central corridor between the classrooms turned out to be the only feature that manifested itself in the temperature of the surface of the roof. The points on the grid were identified by a number for the columns running North-South (vertical in the diagram in Figure 3.1) and a letter for the East-West rows (horizontal in Figure 3.1).

81 copper/constantan thermocouples were imbedded in the surface of the roof to make up a 9x9 square grid with 2 metre separation between thermocouples. The

thermocouples were prepared from standard #26-gauge PCV-coated thermocouple wire. The junctions were welded and a 2-pin connector (Thermo Electric miniature quick-coupling thermocouple connector) was fitted for rapid connect-disconnect to a mating connector which was in turn attached through a short length of thermocouple wire to a portable thermocouple indicator.

Thermal contact between the thermocouple junctions and the surface of the roof was made by softening the surface of the tar with a hand-held propane torch and pressing the junction and about 1 cm. of wire horizontally into the soft tar surface. This technique gave a good mechanical bond and at the same time left the junction in the plane of the surface so its temperature would correspond to the true surface temperature as closely as possible. In most cases, it was necessary to remove one or two gravel stones to expose the tar. After the thermocouple junction was put in place the stones were put back loosely. With the free circulation or air about the gravel, and the relatively high thermal conductivity of the gravel as compared to the high thermal resistance of the insulation below it, most of the temperature gradient from the interior of the building to the outside would occur below the thermocouple. The temperature at the thermocouple junction was assumed therefore to be a close approximation to the surface temperature of the gravel.

After the surface temperature on the dry grid had been measured with the thermocouples and the radiometer, three lanes (on the right side of the diagram) were sprayed with water. The sprayed area is defined by the four corners at A6, A9, I9 and I6 in Figure 3.1. Spraying was begun at the lower (southern) part and proceeded northward. Near the north-east corner of the sprayed area, there was some depressions in the surface which caused very shallow puddles of water to form. The water that collected in these puddles had not frozen completely by the time the remotely-sensed data was acquired.

The local air temperature was measured with a thermocouple mounted 1 meter above the roof surface and located about 3 meters north of the grid.

The shallow rectangular pool was prepared by laying out a 7x10 metre rectangle on the roof near the control grid. A frame of ordinary 5x10 cm. (2"x4") lumber was set down to form the sides of the pool. A double sheet of 0.15 mm-thick polyethylene was laid inside this frame and stapled over its edge to form a shallow water tight tank. Due to the grade on the roof, which fell generally towards the penthouse, the southeast corner of the pool was only half as deep (about 3 cm.) as the northwest corner. The ambient air temperature was several degrees below the freezing point so 27 kg. of rock salt was added to lower the freezing point of the water. This procedure was only partially successful because it proved very difficult to dissolve the salt in the water, even at the temperature at which it came from the filler hose - approximately 10°C. After the first hour of filling, ice began to form on the surface. By constantly agitating the water and ice a well-mixed slurry was maintained, the temperature across the surface of which turned out to be satisfactorily uniform. The surface temperature at the shallowest corner of the puddle appeared to have a very small bias towards being cooler. As a result of the agitation, the temperature was also fairly uniform with depth. At the deep corner the temperature at the bottom was about 1/2°C warmer than the surface. This is not unexpected in view of radiation from the surface, a negative differential of several degrees between the temperature of the surface and the temperature of the air above it, and the presence of some heat flow from the building into the bottom of the pool. Photographs in Figures 3.3 and 3.4 were taken during the preparation of the site. The upper photo in Figure 3.4 is an oblique view of the grid looking southeast. The corners of the grid are marked with lengths of lumber laid on the roof. The lower photo in Figure 3.4 is a view of the rectangular pool taken when it was partially filled. The photo was taken looking generally north in the direction of the penthouse.

3.2 Weather Conditions

The weather conditions under which the thermography and the air photo data were acquired were considered good but not ideal. Local surface winds as recorded at the Charlottetown Airport were approximately 16km/hr. The air temperature at the airport fell slowly from the daytime high of $-3.9^{o}C$ at 10:00 A.M. to $-8.0^{o}C$ after sunset and remained in the -8 to $-9^{o}C$ range until the flight data was taken. The air temperature at the test site was approximately the same; reading -8.2 at 8:30 P.M. and -8.4 at 11:30 P.M. At about 9:00 P.M. the sky was clear except for a thin haze. From the test roof stars were visible through the haze. By the time the remote sensing flight had begun at 11:00 P.M. only the moon was intermittently visible through the haze which had become progressively heavier. According to the records at the Charlottetown Airport, cloud condition at 8:00 P.M. was 1/10 to 5/10 cover at 2,000 feet, 6/10 to 9/10 cover at 12,000 feet and 10/10 cover at 25,000 feet. From the same records the layer reported to be at 2,000 feet at 8:00 P.M. had gone by 9:00 P.M. but the other two layers remained until some time between 11:00 P.M. and midnight. The airport data does not contain an estimate of the density of the cloud cover.

The relative humidity was low and visibility was excellent. From the roof of the building, it was estimated that the visibility was at least 30 miles in any direction. This is in contrast to conditions earlier in the day when the air photos were taken. At that time there was a heavy haze over the city.

The compromise made in the present study in achieving the best balance between optimum weather conditions (ie. cold) and optimum roof conditions (ie. dry and free of snow) can be regarded as typical for data collection in Canada at this time of year. As a case in point, bad weather with precipitation moved into the Maritimes on the day following the experiment with the result that roofs were not dry until almost two weeks later. By this time the ambient air temperature regularly exceeded $0^{o}C$. If a sound basis for collecting data in ambient temperatures above the freezing point could be established, a longer period of acceptable conditions would be achieved. This point is discussed again in later sections. Copies of the meteorological records for the day and for the month are found in Table 3.1.

3.3 Aerial Data

The remotely-sensed data was acquired at 4:00 P.M. and 11:00 P.M., March 26, 1978. Both flights were made at 550 metres ASL with 30% sidelap on adjacent lines and 60% overlap on photographs. The cold and hot black body reference temperatures in the Daedalus scanner, were set at $-7^{o}C$ and $+7^{o}C$ and $-10^{o}C$ and $-2^{o}C$ respectively for the daytime and nighttime thermography.

3.4 On Site Temperature

Thermocouple temperature readings were taken on a DIGIMITE Model 31160 thermocouple indicator. The specified absolute accuracy of the thermocouple wire was $\pm1.5^{o}C$ over the range. The specified accuracy of the DIGIMITE meter, including the internal cold junction compensator, was $\pm1.5^{o}C$ over the range $-150^{o}C$ to $+400^{o}C$.

An independent measurement of five spare thermocouples in a water bath whose temperature was measured with a laboratory alcohol thermometer indicated that the overall accuracy of the thermocouple/indicator system was $\pm0.25^{o}C$. This was to be expected near the middle of the operating range of the system. Wire for the thermocouples was all cut from the same spool to reduce calibration errors among individual units.

A Barnes PRT-5 portable hand-held thermal infrared radiometer was used to measure the local radiant temperatures on the control grid.

Early in the evening of March 26, the thermocouple readings at a few points on the grid were checked against the readings for the radiometer. At one grid point the thermocouple reading was $-5.8^{o}C$ and the radiometer reading was $-5.0^{o}C$. This measurement was taken as evidence that the equipment was functioning correctly. (It was subsequently discovered that the calibration of the radiometer drifted by as much as 2 Centigrade degrees depending upon how long it had been operated in the cold. (See Section 4 for more detail.)

Radiation measurements with the radiometer were made with the sensor head held well away from the operator's body and pointed directly downwards at a distance of about 75 cm. from the surface. The reading on the instrument was relatively insensitive to distance from the surface . The specified field of view of the radiometer is 2°. At 75 cm. above the surface this would yield a sampled spot size of 2 to 3 centimeters depending on the angle of view.

3.5 Data Processing

All remotely-sensed data was processed in Ottawa for subsequent analysis. The data from the thermal IR scanner was converted from magnetic tape to continuous film strips for each flight line. The strips were standard 12.7 cm.-wide negative film with the darkest area corresponding to the warmest targets. An analogue plus an eight level master set and two eight-level subsets were used. Standard 20x25 cm. prints were prepared from the negatives for detailed analysis. Low-contrast paper was found to be essential to preserve the six calibrated grey levels plus black and white on the original negative. Most prints were approximately 6X enlargements from the original negative to give a true scale of about 1000:1. 17X enlargements were also used to study the thermal signature of the control surfaces.

The photographic colour negatives obtained in the daytime flights were reproduced as a roll of 23x23 cm. colour positive transparencies for stereo viewing. The colour transparencies were convenient because black and white prints could readily be made from them with a good enlarger.

It was originally planned to draw a number of isothermal lines through the ground and airborne data to compare results. However, the temperatures were uniform over the surface except at the location of a patch of standing water on the control grid and a more meaningful comparison was made by comparing the features on the thermogram with plots of the surface temperature versus location on the roof.

During the analysis of the data it was found that black and white print enlargements made directly from a colour positive were very useful in studying water and dampness features on roofs. The reversal of the tones in this process has the effect of highlighting the wet and damp areas, making it easier for an analyst to spot subtleties in the photo. A print made in this way can be found with the air photo accompanying Figure 4.6.

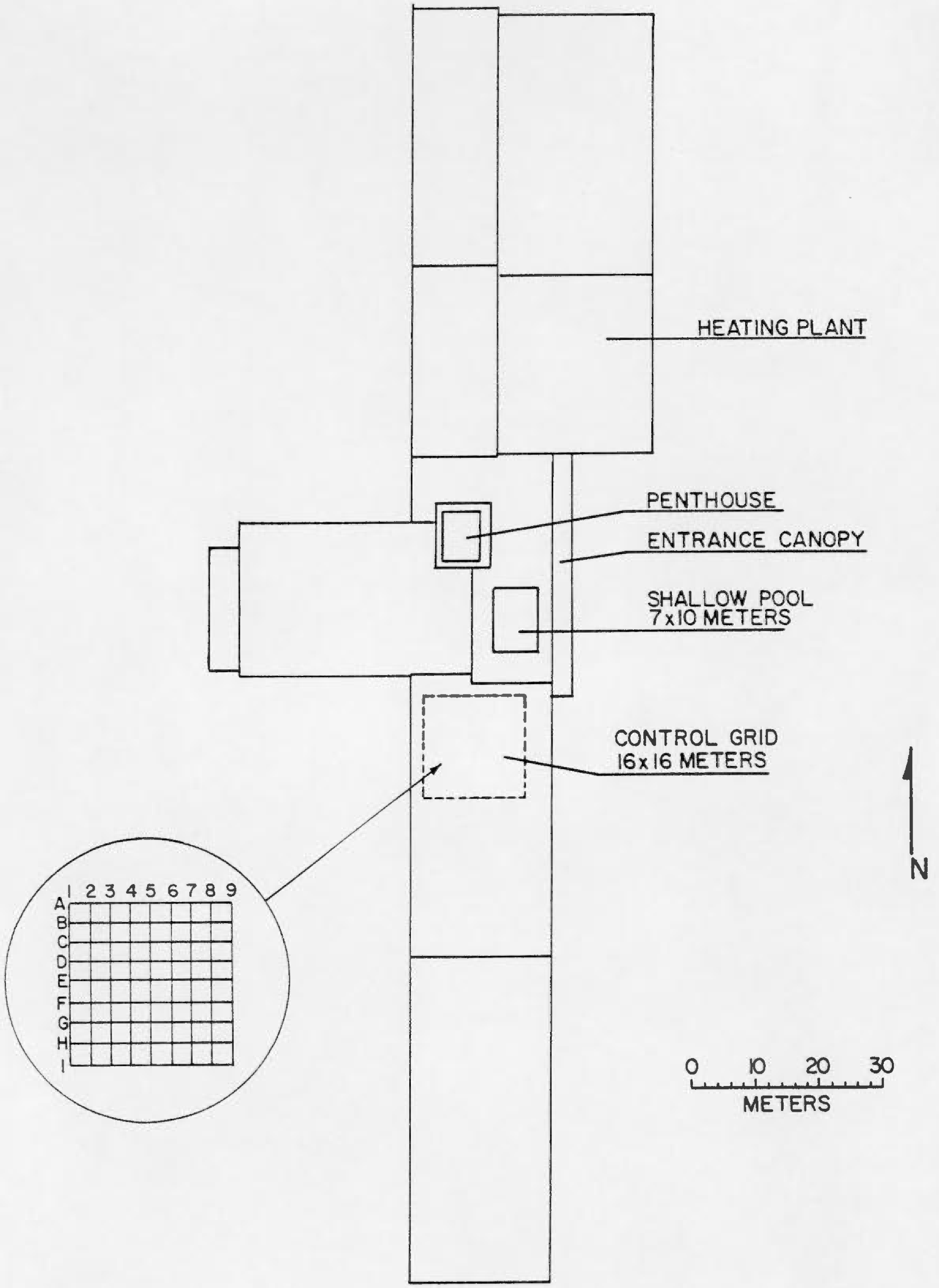


FIG. 3:1 LOCATION OF CONTROL SURFACES ON HOLLAND COLLEGE ROYALTY CENTRE

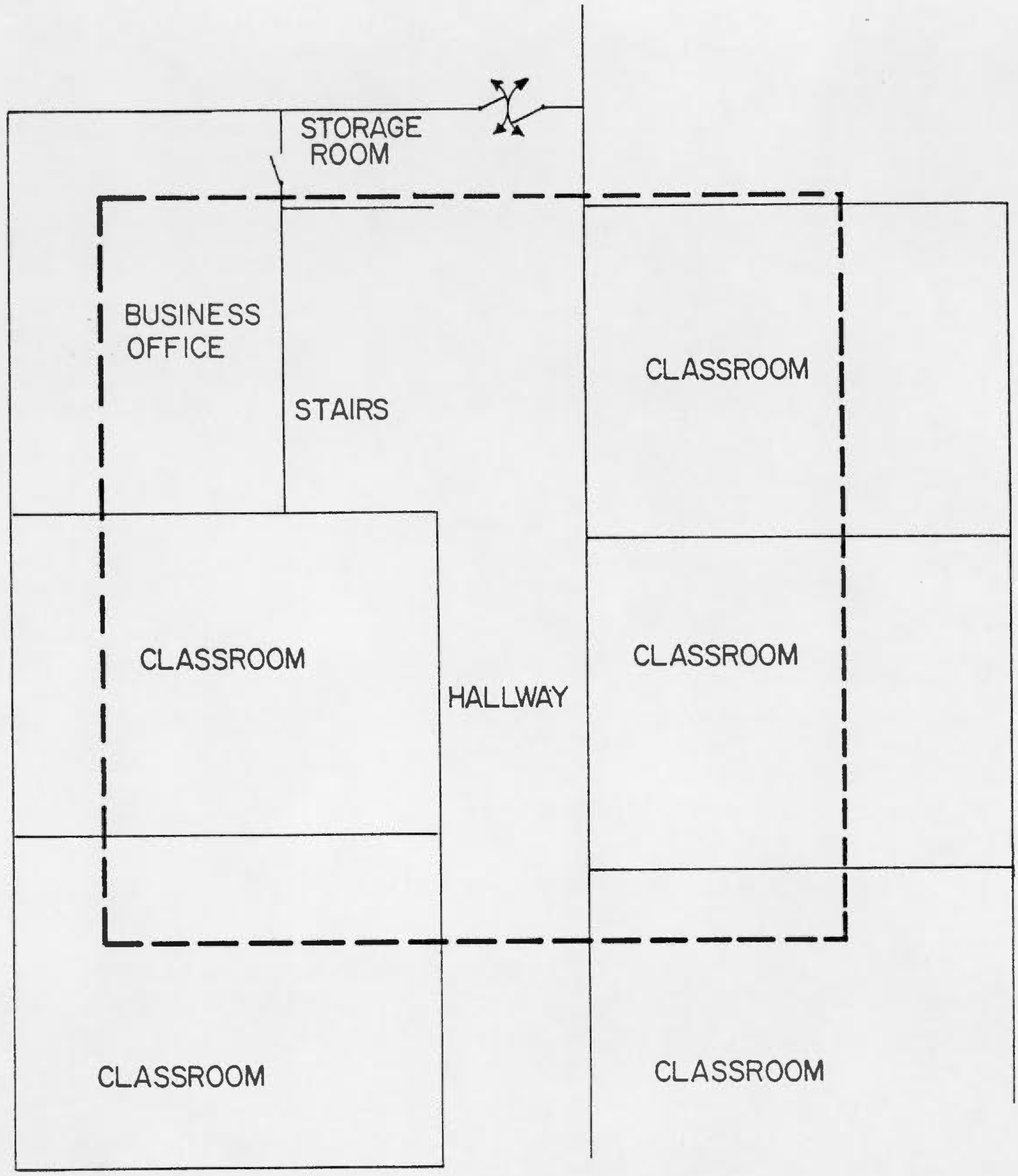


FIG. 3:2 FLOOR PLAN BELOW
81 POINT GRID

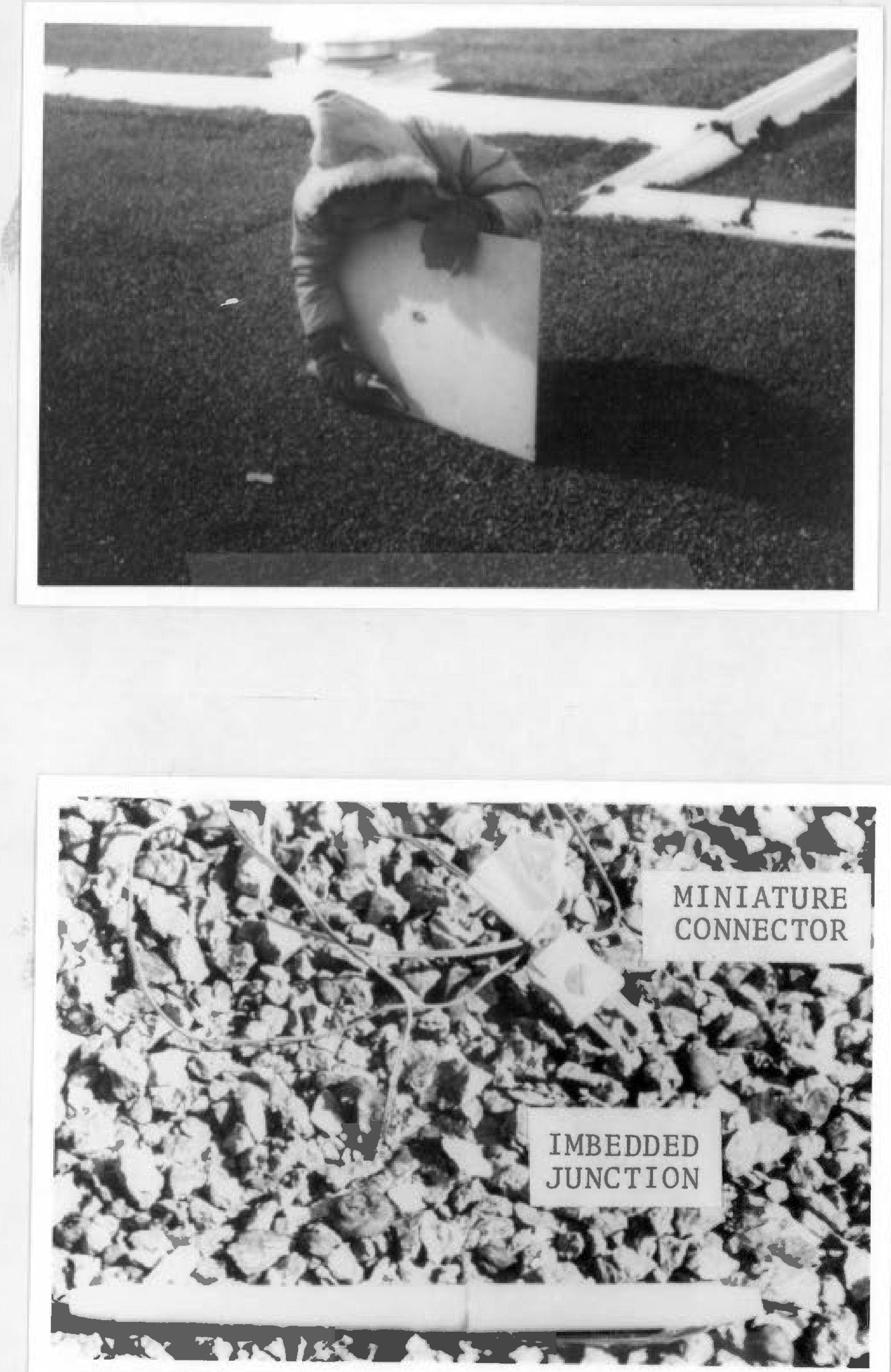


FIG. 3.3 Installation of Thermocouples

FIG. 3.4 Views of Control Surfaces

Table 3.1 HOURLY DATA FOR MARCH 26, and 27, 1978
CHARLOTTETOWN AIRPORT, P.E.I.

DATE	TIME	SKY CONDITIONS/VISIBILITY	TEMP.	RH	WIND
Mar. 26	01:00	CLR/15	-8.6	55	2704
	02:00	CLR/15	-8.7	63	2706
	03:00	CLR/15	-9.0	64	2704
	04:00	CLR/15	-8.9	64	2606
	05:00	CLR/15	-8.6	65	2604
	06:00	CLR/15	-9.0	66	2706
	07:00	CLR/15	-7.9	60	2508
	08:00	200⦶/15	-7.0	59	2808
	09:00	250⦶/15	-5.3	60	3310
	10:00	20⦶250⦷/15	-3.9	49	3314G22
	11:00	20⦶250⦶/15	-4.2	54	3314
	12:00	20⦶250⦷/15	-5.0	63	3612G18
	13:00	20⦶250⦷/15	-5.6	63	3412G18
	14:00	20⦶250⦷/10SW	-5.7	62	0112
	15:00	20⦶250⦷/8SW	-6.2	60	0212
	16:00	20⦶250⦷/10	-6.4	63	0512
	17:00	20⦶250⦷/10	-6.8	63	0212
	18:00	50⦶E250⦷/10	-8.0	64	0515
	19:00	20⦶E120⦷250⊕/10	-8.7	64	0515
	20:00	20⦶E120⦷250⊕/10	-8.8	64	0715
	21:00	E120⦷250⊕/10	-9.0	65	1010
	22:00	E120⦷250⊕/10	-8.9	64	1010
	23:00	E120⦷250⊕/10	-8.6	64	1210
Mar. 27	00:00	E100⊕/10	-8.4	62	1107
	01:00	E100⊕/15	-7.8	65	1207
	02:00	M60⊕/15	-7.2	63	1210
	03:00	M60⊕/15	-7.2	64	1209
	04:00	M34⊕8SW	-7.1	63	1208
	05:00	M22⊕12SW	-6.9	59	1210
	06:00	M22⊕/15	-6.6	61	1107
	07:00	M34⦷250⊕/15	-5.7	64	1309
	08:00	M50⊕/15	-5.1	65	1212
	09:00	E50⦷250⊕/15	-3.8	66	1315
	10:00	E50⦷120⦷/15	-1.8	64	1315
	11:00	25⦶E50⦷120⦷/15	-1.5	64	1320
	12:00	40⦶E120⦷	0.1	61	1315G26

⦶ = 1/10-5/10 Cloud - Scattered

⦷ = 6/10-9/10 Cloud - Broken
⊕ = 10/10 Cloud
M = Measured
E = Estimated

Fisheries and Environment Canada / Pêches et Environnement Canada
Atmospheric Environment / Environnement atmosphérique

MONTHLY METEOROLOGICAL SUMMARY
SOMMAIRE MÉTÉOROLOGIQUE MENSUEL

MONTH/MOIS MARCH/MARS 1978

AT/À CHARLOTTETOWN A, PRINCE EDWARD ISLAND/ILE DU PRINCE EDOUARD

LAT: 46° 17'N LONG: 63° 08'W ELEVATION/ALTITUDE: 172 METRES (ASL) / MÈTRES (NMM) STANDARD TIME USED / HEURE NORMALE UTILISÉE: ATLANTIC / ATLANTIQUE

DATE	TEMPERATURE / TEMPÉRATURE: MAXIMUM / MAXIMALE °C	MINIMUM / MINIMALE °C	MEAN / MOYENNE °C	DEGREE-DAYS / DEGRÉS-JOURS: HEATING / DE CHAUFFE BASE 18.0°C	GROWING / DE CROISSANCE BASE 5.0°C	REL. HUMIDITY / HUMIDITÉ REL.: MAXIMUM / MAXIMALE %	MINIMUM / MINIMALE %	THUNDERSTORM / ORAGE	PRECIPITATION / PRÉCIPITATIONS: RAINFALL / PLUIE (HAUTEUR) mm	SNOWFALL / NEIGE (HAUTEUR) cm	TOTAL PRECIP. / PRÉCIP. TOTALE mm	SNOW ON GROUND / NEIGE AU SOL cm	WIND / VENT: AVERAGE SPEED / VITESSE MOYENNE km/h	PREVAILING DIRECTION / DIRECTION DOMINANTE	MAXIMUM SPEED AND DIRECTION / VITESSE MAXIMALE ET DIRECTION km/h	BRIGHT SUNSHINE / INSOLATION EFFECTIVE HOURS / HEURES
1	-2.7	-15.0	-8.9	26.9		89	76			2.0	1.8	51	10.4	W	WNW 22	5.6
2	-4.5	-15.2	-9.9	27.9		91	65			1.3	1.3	50	12.7	WNW	NW 33	4.6
3	-2.8		-6.0	24.0		83	66			TR	TR	50	20.7	WNW	NW 28	3.0
4	-4.0	-8.3	-6.2	24.2		87	80			18.8	18.4	51	23.5	ENE	NW 46	
5	-8.0	-14.4	-11.2	29.2		80	58			0.4	0.4	65	33.1	W	NW 40	2.3
6	-6.8	-14.4	-10.6	28.6		78	55			1.2	1.0	65	35.8	W	W 46	0.6
7	-2.0	-7.8	-4.9	22.9		81	53			2.0	2.0	65	28.6	WNW	WNW 33	1.3
8	-4.4	-11.5	-8.0	26.0		69	47			TR	TR	65	19.5	N	NW 33	8.9
9	-2.3	-11.5	-6.9	24.9		74	52					64	18.1	WNW	NW 28*	9.4
10	3.0	-7.0	-2.0	20.0		83	57			TR	TR	58	23.5	Svrl	SW 36	6.0
11	-4.3	-11.2	-7.8	25.8		85	70			TR	TR	52	27.9	NE	NE 41	4.0
12	1.9	-9.7	-3.9	21.9		92	80		0.2	1.6	1.8	50	19.4	SW	S 28	
13	0.0	-7.4	-3.7	21.7		77	44					42	19.7	N	NNW 33	9.5
14	4.1	-7.5	-1.7	19.7		87	60					42	22.1	SSE	SSE 43	5.9
15	5.4	0.1	2.8	15.2		94	81		4.0		4.0	34	22.8	SW	SE 37	0.5
16	0.4	-10.1	-4.9	22.9		90	51			2.2	2.0	25	21.8	WNW	NW 37	7.6
17	-6.6	-13.7	-10.2	28.2		81	71			8.0	7.6	26	22.5	Svrl	NNE 33*	
18	-2.7	-15.7	-9.2	27.2		79	47					32	17.0	W	SW 28	8.8
19	1.0	-13.6	-6.3	24.3		82	47			0.7	0.7	31	22.5	S	S 37	
20	1.2	-9.6	-4.2	22.2		85	47			3.0	2.8	32	28.3	W	W 40	9.7
21	4.9	-11.2	-3.2	21.2		94	59		4.0	3.0	7.2	32	18.6	S	S 33	1.5
22	6.7	-3.4	1.7	16.3		96	76		1.2	TR	1.2	29	24.3	S	S 33	0.3
23	2.0	-5.1	-1.6	19.6		85	60			0.5	0.6	23	12.4	E	NW 28	6.1
24	4.6	-6.2	-0.8	18.8		88	62			0.5	0.6	21	17.9	E	WNW 37	3.8
25	-3.6	-8.6	-6.1	24.1		75	49			0.6	0.6	20	26.6	WNW	WNW 33	10.0
26	-3.7	-9.5	-6.6	24.6		69	59			TR	TR	20	17.7	W	NNW 28	9.5
27	3.4	-7.3	-2.0	20.0		[illegible]	45		TR	TR	TR	18	24.8	SE	SE 37	0.4
28	6.9	1.3	4.1	13.9		[illegible]	68		2.8		2.8	14	24.6	WSW	SE 39	0.0
29	5.4	-2.2	1.6	16.4		81	66		TR		TR	11	14.8	Svrl	W 22	2.6
30	-1.0	-5.7	3.4	21.4		77	68			TR	TR	11	17.3	N	NW 30	5.0
31	3.1	-6.3	-1.6	19.6		78	61					11	7.2	S	SSW 15*	10.2
MEAN / MOYENNE	-0.2	-8.9	-4.6	TOTAL 707.6	TOTAL	84	61	TOTAL	TOTAL 12.2	TOTAL 45.8	TOTAL 55.0		21.2	PREVAILING W DOMINANTE	MAXIMUM W 46	TOTAL 137.1
NORMAL / NORMALE	0.4	-6.7	-3.2	656.7	0.9			0	31.8	51.8	84.6		21.9	W		137

DEGREE-DAY SUMMARY – SOMMAIRE DE DEGRÉS-JOURS

BELOW 18°C / AU-DESSOUS DE 18°C	THIS YEAR / ANNÉE EN COURS	PREVIOUS YEAR / ANNÉE PRÉCÉDENTE	NORMAL / NORMALE	ABOVE 5°C / AU-DESSUS DE 5°C	THIS YEAR / ANNÉE EN COURS	PREVIOUS YEAR / ANNÉE PRÉCÉDENTE	NORMAL / NORMALE
TOTAL FOR MONTH / TOTAL DU MOIS	707.6	586.6	656.7	TOTAL FOR MONTH / TOTAL DU MOIS	0.	1.4	0.9
ACCUMULATED SINCE JULY 1 / ACCUMULÉE DEPUIS LE 1er JUILLET	3816.4	3948.9	3735.7	ACCUMULATED SINCE APRIL 1 / ACCUMULÉE DEPUIS LE 1er AVRIL	1743.6		1651.1

	DAYS WITH TOTAL PRECIPITATION: / JOURS AVEC PRÉCIPITATIONS TOTALES: mm					DAYS WITH SNOWFALL: / JOURS AVEC CHÛTE DE NEIGE: cm				
	0.2 OR MORE – OU PLUS	1.0 OR MORE – OU PLUS	2.0 OR MORE – OU PLUS	10.0 OR MORE – OU PLUS	50.0 OR MORE – OU PLUS	0.2 OR MORE – OU PLUS	1.0 OR MORE – OU PLUS	2.0 OR MORE – OU PLUS	10.0 OR MORE – OU PLUS	50.0 OR MORE – OU PLUS
	18	13	8	1	0	15	10	7	1	0

UDC 551.506.1 ( )

Subscription Price: $1.00 monthly; $10.00 per calendar year (January to December)
Prix d'abonnement: mensuel $1.00; annuel $10.00 (janvier à décembre)

DRY-BULB TEMPERATURE SUMMARY*
SOMMAIRE DES TEMPÉRATURES DU THERMOMÈTRE SEC*

MONTH / MOIS: MARCH / MARS

1978

	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	-29	-26	-29	-31	-33	-38	-42	-54	-57	-53	-58	-58	-60	-62	-57	-47	-50	-55	-76	[illegible]	-88	-96	-101	-106
	-110	-148	-129	-150	-153	-131	-122	-116	-103	-95	-91	-89	-82	-71	-65	-61	-57	-64	-68	-71	-63	-44	-49	-61
	-71	-76	-71	-76	-73	-72	-69	-71	-72	-73	-68	-54	-45	-37	-31	-29	-28	-26	-44	-61	-65	-78	-80	-69
	-73	-77	-79	-71	-82	-76	-76	-69	-67	-63	-52	-52	-51	-43	-50	-49	-47	-49	-47	-49	-47	-46	-46	-59
	-62	-76	-82	-90	-93	-104	-112	-120	-122	-121	-124	-121	-114	-108	-104	-101	-92	-90	-92	-99	-104	-113	-119	-126
	-134	-143	-143	-138	-134	-135	-134	-134	-134	-132	-127	-116	-109	-101	-98	-92	-91	-86	-86	-85	-79	-71	-70	-76
	-77	-79	-76	-72	-69	-68	-67	-66	-63	-59	-59	-52	-42	-33	-33	-33	-27	-38	-46	-50	-55	-54	-48	-47
	-49	-51	-55	-60	-64	-65	-65	-66	-72	-57	-54	-53	-48	-50	-48	-53	-52	-60	-66	-74	-76	-84	-87	-94
	-111	-109	-103	-99	-74	-84	-96	-96	-90	-74	-66	-54	-46	-34	-32	-31	-27	-33	-35	-39	-35	-36	-36	-38
	-34	-29	-24	-17	-11	-02	-07	-03	-07	-04	00	13	19	22	23	17	16	00	-18	-26	-36	-49	-56	-61
	-59	-54	-61	-64	-69	-71	-72	-72	-71	-61	-55	-46	-50	-45	-50	-49	-51	-52	-62	-68	-79	-82	-94	-99
	-101	-107	-98	-87	-94	-83	-84	-72	-49	-36	-24	-11	-04	02	10	17	13	07	08	07	12	10	06	07
	07	11	-01	-12	-22	-39	-41	-48	-46	-44	-46	-48	-47	-43	-41	-44	-38	-30	-44	-63	-59	-53	-72	-67
	-72	-65	-66	-64	-54	-71	-69	-71	-62	-37	-23	-04	08	38	36	31	28	22	13	-01	-08	-07	01	09
	16	20	24	31	35	39	40	47	48	52	40	41	31	38	33	32	27	29	32	22	21	20	17	13
	13	11	10	-01	-09	-19	-31	-35	-43	-52	-58	-57	-58	-51	-43	-39	-38	-37	-53	-54	-59	-65	-74	-74
	-81	-83	-75	-81	-76	-73	-74	-73	-76	-76	-74	-73	-72	-68	-74	-79	-76	-80	-86	-92	-98	-106	-107	-109
	-124	-135	-132	-148	-140	-139	-146	-129	-91	-75	-66	-56	-43	-38	-35	-30	-31	-33	-30	-35	-44	-59	-68	-75
	-75	-89	-91	-98	-99	-109	-133	-117	-94	-66	-44	-34	-25	-12	-12	-09	-08	-07	03	06	08	00	-05	02
	03	02	06	04	-11	-19	-57	-79	-83	-84	-80	-77	-72	-67	-64	-58	-55	-56	-59	-71	-68	-82	-83	-89
	-94	-81	-83	-76	-77	-111	-94	-87	-70	-35	-27	-16	-07	-21	-17	-08	-02	06	17	31	42	37	33	34
	47	44	41	36	51	49	47	46	51	51	52	59	56	51	51	40	33	36	34	13	-10	-18	-18	-21
	-21	-21	-23	-30	-31	-33	-44	-42	-36	-21	-09	02	03	05	04	12	16	-02	-06	-07	-04	-06	-09	[illegible]
	-11	-14	-14	-13	-11	-07	-09	-10	-08	-03	03	-9	11	21	32	22	44	41	29	-06	-06	-11	-15	[illegible]
	-43	-54	-59	-63	-67	-68	-70	-77	-77	-76	-67	-61	-56	-47	-42	-38	-41	-39	-45	-51	-56	-58	-64	[illegible]
	-70	-86	-87	-90	-89	-86	-90	-79	-70	-53	-39	-42	-50	-56	-57	-62	-64	-68	-80	-87	-88	-90	-89	[illegible]
	-84	-78	-72	-72	-71	-69	-66	-57	-51	-38	-18	-15	01	03	07	09	09	09	08	07	04	02	04	10
	10	18	26	39	52	51	51	53	52	61	60	59	59	51	48	49	41	33	28	23	23	26	22	17
	16	16	19	12	11	11	11	12	11	19	21	23	28	33	36	46	52	46	44	31	29	31	29	05
	-08	-12	-18	-16	-18	-18	-26	-28	-27	-26	-15	-16	-17	-13	-19	-14	-16	-18	-21	-23	-31	-41	-50	-50
	-55	-53	-56	-49	-59	-64	-56	-56	-43	-19	-10	-17	-06	03	12	21	27	26	21	-01	-12	-16	-19	[illegible]

*Temperatures in tenths of degrees Celsius — Températures en dixième de degrés Celsius

	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23

WIND SUMMARY (Kilometres per hour)
SOMMAIRE DES VENTS (Kilomètres par heure)

MONTH / MOIS: MARCH / MARS — 1978

Date	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Peak Gust / Rafale maximum	Hour / Heure
1	C	C	W 3	WSW 13	W 9	W 19	W 15	W 15	WNW 15	WNW 22	WNW 13	W 15	W 15	W 15	W 17	W 15	WNW 5	NW 6	NW 9	C	S 3	SW 7	SW 9	WSW 9		
2	WSW 7	C	S 7	SSW 7	WSW 11	WSW 7	WNW 7	W 5	C	NNW 11	NW 9	WNW 11	WNW 9	WNW 7	WNW 19	WNW 17	NW 15	NNW 9	WNW 19	W 19	WNW 19	NW 28	NW 28	NW 33	NW 52	2300
3	NW 28	NW 28	NW 28	WNW 28	WNW 22	WNW 28	W 28	WNW 28	WNW 28	NW 28	WNW 28	WNW 28	WNW 28	WNW 19	WNW 19	WNW 26	WNW 19	W 13	C	SW 7	SW 9	SW 7	SW 7	SW 13	WNW 46	0700
4	S 9	SSW 9	SE 6	S 11	ESE 7	ESE 9	SSE 9	ENE 5	E 15	E 15	E 22	E 32	ENE 28	ENE 28	ENE 36	ENE 33	NE 33	NNE 33	N 33	N 33	N 33	NNW 33	NW 46	NW 46	NW 72	2300
5	NW 40	WNW 33	WNW 33	WNW 33	WNW 33	W 33	W 33	W 33	W 33	W 28	W 28	W 37	W 33	W 37	WSW 37	W 33	WSW 30	WSW 33	W 33	W 33	W 37	W 33	W 26	W 33	W 59	1100
6	WSW 33	WSW 33	WSW 36	WSW 36	W 46	W 37	W 37	W 37	W 37	W 37	W 33	W 37	W 37	W 37	W 26	W 37	W 37	WNW 41	WNW 41	WNW 33	WNW 33	WNW 33	WNW 33	WNW 33	W 74	1300
7	WNW 33	W 30	WNW 28	WNW 30	WNW 30	WNW 28	W 26	WNW 28	WNW 30	WNW 28	WNW 26	WNW 26	NW 28	NW 26	NW 30	NW 26	NW 33	N 28	N 28	N 28	NNW 28	N 33	NNW 28	NNW 28	NW 52	1400
8	NW 19	NNW 26	N 26	N 22	N 26	N 22	N 30	NNW 22	N 22	N 28	NW 33	NNW 28	N 28	NNW 19	NW 22	NW 22	NW 15	NW 11	C	C	S 11	S 15	S 11	S 11		
9	SW 9	SW 9	W 15	WNW 19	NW 22	WNW 13	WNW 19	NW 22	NW 28	WNW 19	WNW 22	W 15	W 13	SW 13	SW 22	S 9	SSE 11	S 13	S 26	SW 22	SSW 19	SSW 19	SW 28	SW 28		
10	SW 28	SW 33	SW 36	SW 22	WSW 33	WSW 28	W 19	WSW 28	WSW 28	WSW 22	WSW 19	WSW 11	W 15	NW 9	N 11	N 19	N 26	NE 22	NE 22	NE 22	NE 28	NE 28	NE 28	NE 26	SE 46	0400
11	NE 22	NE 33	NE 37	NE 41	NE 37	NE 33	NE 33	NE 33	NE 33	NNE 30	NNE 30	NNE 33	NE 33	N 33	N 33	N 33	N 33	N 28	N 32	N 19	N 11	NW 7	WNW 7	W 5	NE 56	0700
12	C	SW 9	SW 13	S 15	S 19	S 19	S 19	S 28	SW 26	SSW 22	S 26	S 22	SSW 22	SW 22	SW 32	SW 22	SW 22	SW 19	SW 19	WSW 28	SW 19	SW 15	WSW 11	W 17		
13	W 17	NW 26	NW 28	NW 28	NNW 33	N 28	N 26	N 22	N 22	N 26	N 28	N 24	N 22	N 20	N 22	N 15	NNW 9	N 7	SW 6	SSW 13	SW 11	SW 9	SSW 15	SW 15	NNW 44	0300
14	SW 9	SW 13	SW 11	SW 11	S 11	S 7	S 7	S 26	S 19	SSE 15	S 17	SE 15	SSE 19	SSE 24	SSE 28	SSE 28	SSE 28	SSE 28	SE 28	SSE 37	SSE 37	SSE 43	SSE 37	SSE 33	SSE 63	2100
15	SSE 28	S 28	SE 28	SE 37	SSE 37	SE 33	SSE 33	SSE 33	S 33	SSW 28	SW 28	SSW 19	WSW 19	SW 19	SW 19	SW 22	SW 15	SW 9	SW 11	WSW 9	WSW 13	W 13	W 19	WSW 13	SE 55	0300
16	W 15	WSW 17	WNW 28	NW 28	NW 37	NW 19	NW 28	NW 28	WNW 37	WNW 33	WNW 28	WNW 28	WNW 33	WSW 28	WNW 22	NW 19	NW 13	N 15	NNW 11	N 9	NE 7	N 7	N 15	N 17	NW 56	0400
17	N 22	NNW 11	N 6	N 9	NE 13	ENE 13	ENE 28	ENE 19	ENE 28	NE 22	NE 28	NE 28	NE 30	NE 32	NNE 33	NNE 33	N 33	NNE 28	NNE 26	N 26	N 22	NW 19	NW 15	NW 15	N 48	1600
18	W 9	W 9	W 11	W 9	W 9	WSW 7	WSW 13	SW 9	SW 11	SW 19	SW 26	WSW 22	WSW 22	SW 26	SW 26	SW 28	SW 28	SW 28	WSW 28	W 22	W 15	W 22	W 13	WNW 17	SW 46	1500
19	WNW 15	WNW 13	NW 15	WNW 9	W 7	SSE 9	SE 11	SE 11	SE 19	SSE 26	SSE 26	S 33	S 26	S 33	S 33	S 33	S 37	S 33	SSW 28	SW 28	SW 28	WSW 19	WSW 20	SW 26	S 59	1300
20	SW 22	SW 22	SW 22	SW 26	W 22	W 33	W 37	W 40	W 37	W 37	W 37	W 37	W 37	WNW 37	W 37	W 33	W 26	W 22	W 22	W 30	W 26	W 11	W 11	W 15	W 80	0600
21	WSW 9	SW 15	SW 9	SW 9	S 9	ESE 11	SSE 19	SSE 19	S 19	SSW 26	S 33	S 22	S 22	S 26	S 26	SSE 33	SE 28	SE 22	S 22	SSW 22	SW 19	SSE 11	S 19	SSW 15	SE 52	1400
22	SW 22	SW 14	S 9	S 13	S 19	S 22	S 29	S 28	S 28	S 32	S 33	S 32	SSW 33	WSW 28	SSW 32	WSW 22	WSW 22	WSW 22	W 22	NW 22	NW 26	NW 28	NW 22	NW 22	S 52	0900
23	NW 28	NW 19	WNW 19	WNW 19	WNW 13	W 9	W 11	W 11	WNW 11	WSW [illegible]	W 7	SSW 7	SSW 9	S 13	SW 9	ESE 7	E 7	SSW 19	ESE 7	E 11	ESE 11	E 15	E 15	E 11		
24	E 15	E 19	E 19	E 13	E 9	E 17	ESE 15	ESE 9	ESE 11	ESE 11	[illegible] 7	S 15	S 11	SW 17	SW 11	WSW 15	SW 19	SW 15	S 28	WNW 37	WNW 22	W 33	W 28	W 33	W 59	2100
25	W 33	W 33	WNW 33	WNW 33	NW 33	WNW 33	WNW 26	WNW 22	WNW 28	WNW 28	NW 24	WNW 19	WNW 28	NW 28	NW 28	WNW 33	WNW 26	WNW 28	WNW 22	WNW 22	NW 19	NW 19	NW 22	WNW 19	W 52	0300
26	WNW 11	W 7	W 11	W 7	W 11	W 7	W 11	WSW 13	W 15	NW 19	NW 26	NW 26	N 22	NNW 28	N 22	NNE 22	N 22	NNE 22	NE 28	NE 28	ENE 9	E 19	E 19	ESE 19	NW 41	1000
27	ESE 13	ESE 13	ESE 19	ESE 17	ESE 15	ESE 19	ESE 13	SE 17	ESE 22	SE 28	SE 28	SE 17	SE 28	SE 37	SE 37	SE 37	SE 28	SE 28	SE 33	SE 33	SE 33	SE 28	SE 28	SE 28	SE 52	2300
28	SE 37	SE 37	SE 37	SE 39	SE 37	S 37	SSE 20	S 28	S 22	S 28	S 19	SSW 13	SSW 19	WSW 13	SSW 19	WSW 19	WSW 22	WSW 19	WSW 22	WSW 22	WSW 22	W 15	W 22	W 22	SE 58	0100
29	W 22	W 19	W 19	WSW 9	WSW 13	WSW 19	WSW 19	SW 15	SW 15	WSW 17	15	SW 7	SW 15	WSW 15	SW 19	WSW 19	SW 19	SW 15	SW 11	WSW 11	WSW 11	W 9	N 7	NNW 15		
30	E 6	N 7	C	N 19	N 15	N 26	N 26	NNW 26	NNW 22	NW 19	NW 30	NNW 26	NW 22	NW 22	NNW 22	NNW 26	N 24	NW 28	N 15	N 15	N 9	NE 6	ENE 5	C	NNW 32	0700
31	W 7	WSW 7	WNW 7	WNW 7	C	C	C	C	C	S 11	SSE 11	SSW 15	[illegible] 15	S 11	SE 9	ESE 9	ESE 9	SE 9	S 9	S 11	S 7	S 9	S 15	SW 9		

On indique un vent d'ouest par la lettre 'W'.

*Indicates later occurrences of same speed
*Indique des données postérieures de la même vitesse.

DAILY CLIMATOLOGY SUMMARY MARCH 1978

1. Overcast with snow clearing by mid evening.
2. Clear, clouding over by mid morning. Flurries evening.
3. Overcast with flurries ending by mid morning and clearing by evening.
4. Overcast with flurries and blowing snow.
5. Cloudy with flurries and blowing snow clearing by mid morning.
6. Cloudy with snow and blowing snow.
7. Overcast with flurries. Clearing late evening.
8. Mainly clear. Few afternoon cloudy periods with flurries.
9. Cloudy clearing mid morning then clouding over by mid afternoon.
10. Overcast with flurries clearing by late morning.
11. Cloudy. Flurries in the mid afternoon clearing by late evening.
12. Clear, clouding over with flurries in the morning. Rainshowers and flurries in the evening.
13. Cloudy, clearing by mid morning.
14. Clear. Clouding over in the afternoon.
15. Overcast with rain and drizzle in the morning ending early in the afternoon. Fog and rain in the eveing.
16. Overcast with flurries. Clearing by mid afternoon. Becoming overcast by evening.
17. Overcast with flurries in the morning becoming snow and blowing snow by late morning. Flurries in the evening clearing by late evening.
18. Clear.
19. Clear becoming overcast with flurries by mid morning. Brief clearing in the mid evening.
20. Overcast with flurries and blowing snow clearing near noon.
21. Clear, clouding over near noon with flurries becoming rain and rainshowers by evening.
22. Overcast with rainshowers late in the morning and late afternoon. Flurries in the evening.
23. Clearing in the morning becoming overcast by late morning. Flurries in the evening.
24. Overcast with flurries in the morning and evening.
25. Overcast with flurries clearing early in the morning.
26. Clear clouding over early in the afternoon with flurries.
27. Overcast. Flurries in the morning, rainshowers in the evening.
28. Overcast with rainshowers and fog in the morning. Drizzle by mid evening.
29. Overcast with rianshowers near noon. Clearing in the afternoon.
30. Overcast with flurries and fog clearing in the evening.
31. Mainly clear. Seasonable temperatures.

MONTHLY CLIMATOLOGICAL SUMMARY MARCH 1978

Both temperature and precipitation amounts were below normal. The mean temperature of 8.9°C was 2.2°C below normal. Both the mean maximum and mean minimum temperatures for the month were below normal.

Total precipitation of 55 mm amounted to 75% of the normal. Rainfall amounts were well below normal with the 12.2 mm of rain received representing only 40% of the normal while the total snowfall accumulation of 45.8 cm was 10% below normal. Only one major snowfall was received during the month when 18.8 cm of snow fell on the 4th.

Winds speeds were near normal for the m h. Sunshine hours were normal. Blowing snow was common during the month and was reported on the 4th, 5th,6th,16th,17th,19th,20th and 24th. Fog was reported on the 15th, 21st, 28th and 30th. Both freezing rain and ice pellets occurred on the 21st.

No new records were established during the month.

4. Quantitative Results for the Control Site

4.1 Ground Truth Data

The measured temperatures on the control grid are shown in Figure 4.1 through 4.4. The data in Figures 4.1 and 4.2 were taken approximately two hours after dark; that in Figure 4.3 and 4.4 was begun ten minutes after the remote sensing flight and took 20 minutes. The measurements on the rectangular pool are shown in Figure 4.5. The data for the pool were taken immediately after the remote sensing flight. Graphs of the physical surface or contact temperature and the radiant temperatures for the points in row G, as measured by the thermocouples and the PRT-5 radiometer, are presented in Figures 4.11 and 4.12. The temperatures in Figure 4.11 are taken from the data in Figures 4.1 and 4.2, that is a totally-dry grid. The temperatures in Figures 4.12 are taken from Figures 4.3 and 4.4, that is the partially-sprayed grid. Figure 4.13 is a set of four graphs of temperatures versus position for the four south rows of the grid, rows F,G,H, and I. The data are taken from Figure 4.1 and 4.3, the thermocouple measurements over the totally-dry and partially-sprayed grid respectively.

At the beginning of the first set of measurements on the grid the local air temperature was $-8.2^{\circ}C$. By the time the measurement was finished, about thirty minutes later, the temperature had fallen $2/10^{\circ}C$ to $-8.4^{\circ}C$. During the second set of measurements - ie. the set that correlates with the airborne data - the air temperature was steady at $-8.4^{\circ}C$.

The radiant sky temperature was measured with the radiometer about one half to one hour before the remote sensing flight; the exact time was not logged. No attempt was made to map the sky temperature, a small number of measurements were made in random directions. The readings were consistent at $-18^{\circ}C$. When these readings were being taken the cloud cover was uniform with the shape of the moon barely discernible.

When the PRT-5 radiometer data had been plotted some four weeks after the experiment had been done it was observed that the calibration of the instrument was drifting slightly while the readings were being taken. The rate at which the drift occurred and the point at which the radiometer was in correct calibration could not be determined after the fact. The radiometer readings on the grid were taken a row at a time, starting with point A-1 of row 1. Comparison of the trend in measured radiant temperature across rows 1 and 2 of the grid in Figure 4.2 with the thermocouple temperatures in Figure 4.1 for the same points, show that the radiometer calibration drifted most rapidly at first. The same comparison for, say rows 2 and 3 shows much less drift. The rapid drift is also seen in the data in Figure 4.5. The radiometer data in Figure 4.5 was taken in less than 5 minutes and was followed by the measurements on the grid. Prior to use at 8:30 P.M. and 11:20 P.M. the PRT-5 was kept in the warm penthouse of the building with the internal battery on "charge".

For the foregoing reason, the data in Figures 4.2 and 4.4 is believed to be reliable from the point of view of the radiometer temperature trend along the rows, except for the first one or two rows, but the accuracy is reduced and there is a fixed-bias error.

4.2 Remotely-Sensed Data

Figures 4.6 through 4.10 are the thermograms prepared from the remotely-sensed data. The temperature calibration for the density levels in the prints have been shown directly on the thermograms for convenience. Some specific temperature levels have also been marked on Figures 4.8 and 4.10. The rectangular pool and the 81-point grid are outlined on Figure 8. The outlines are approximate due to the coarseness of the scanner data at this scale and some geometric distortion. Figures 4.6, 4.7, and 4.9 are to an absolute scale of approximately 1200:1; Figure 4.8 shows only a portion of the building and is to a scale of approximately 424:1. Figure 4.9 is a result of a special run on the Daedalus ground processor. In Figure 4.9 the data is in regular analogue format except that all points in the scene at a pre-selected temperature, in this case points in the $0^{o}C$ to $2^{o}C$ band, are intensified to black on the negative and appear white on the print.

4.3 Discussion of Results

The first set of temperatures taken when the grid was totally dry, Figures 4.1, and 4.2, 4.11, and parts of 4.13 indicate that the roof was at a uniform temperature without any serious anomalies. The hallway in the building lay under the lower (southern) half of the grid between column 4 and 7. A temperature drop of about 1/2^{o}C over this hallway, and a slight drop towards the edge of the bulding can be discerned by examining the graphs for row G in Figure 4.11, taken when the grid was dry, and the solid-line graphs in Figure 4.13.

The surface temperature of the roof, as measured by the thermocouples, is warmer than the local air temperature as would be expected but the two are within a degree of each other. In 1977 the surface and air temperatures were within 1/2^{o} of each other.

The second set of temperature measurements on the grid, shown in Figure 4.3, 4.4, 4.12 and part of 4.13 correspond to the thermal conditions on the roof approximately 15 minutes after the airborne data was collect. It is obvious from the data that rows F,G.H. and I of the grid stabilized thermally between the time the spraying ended and the data was taken and that rows A though E did not. The upper right section of the grid has a large warm region indicative of the lingering effect of the warm water. This is confirmed in the thermograms.

In the first part of this analysis, attention is focused on the section of the grid that stabilized. The basic data is in Figure 4.13. (Note 1).

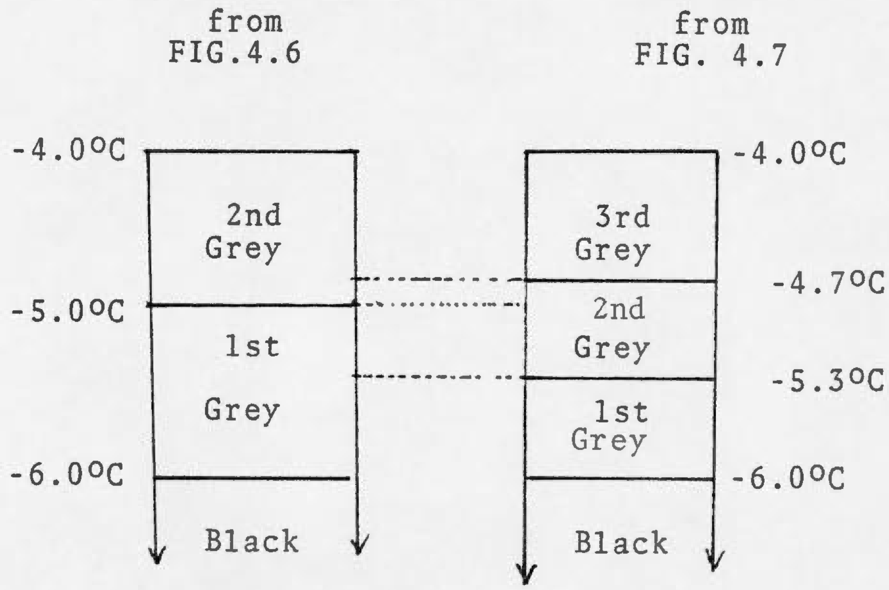
Note 1:The PRT-5 readings are not included in this section of the analysis because of doubtful accuracy.

The roof shows an overall warmer temperature after 11:00 P.M. when the airborne data and the second set of in-situ measurements were taken than it does at 8:30 P.M. when the first measurements were made. This temperature rise is attributed to the denser cloud cover and increased radiant heating from the sky since the ambient air temperature was approximately the same both times. In fact the ambient air temperature fell a few tenths of a degree between the time the two sets of readings were taken although it recovered to the initial value by the time the second set was taken.

The dry section of the roof shows a more pronounced temperature rise than the sprayed section. Simple averages were taken for temperature increase at the two sections to estimate this rise. For the dry section, rows F to I, columns 1 to 5, the average increase is 0.59^{o}C. For the sprayed section, rows F to I, columns 6 to 9, the average increase is 0.36^{o}C. The difference between the two averages is 0.23^{o}C with the sprayed portion being the coolest. The increased emissivity of the ice surface would be a factor in this surface remaining cooler. Noting that the "sprayed" surface was initially warmed up because the water was well above the freezing point, the radiant cooling appears to have been very effective.

The aerial thermograms for the lower part of the grid show a contrast change from the dry to sprayed portion which is the reverse of the actual surface temperature condition. The contrast change is small enough to cause only a change from one temperature band to the adjacent band in a level-sliced thermogram so the radiant temperature change is small. However, by using two different level-sliced thermograms, the actual difference can be estimated.

Part of the temperature vs. density code for the level-slicing used for the thermograms in Figures 4.6 and 4.7 is reproduced below:



In both thermograms, the radiant temperature of the dry portion of the grid falls in the 1st grey level. The radiant temperature is therefore between -6.0°C and -5.3°C. The radiant temperature of the sprayed portion of the grid falls in the second grey level in both thermograms except for a small wedge in Figure 4.7 near the bottom of the grid where the temperature shifts back into the lower band. Neglecting this small part for the moment the radiant temperature of the sprayed section is between -5.0°C and

-4.7^{o}C. Thus the change in contrast from the dry to the sprayed portion indicates a radiant temperature change ranging from a minimum of 0.3 to a maximum of 1.3 degrees (C). Taking a simple average gives 0.8^{o}C. Returning now to the fact that a small wedge of the sprayed section falls into the 1st grey level in Figure 4.6, one concludes that the radiant temperature of the sprayed section must be close to the cross-over temperature of -5^{o}C between the bands, perhaps 5.1^{o}C. The likely maximum temperature spread therefore is 1.1 instead of 1.3 degrees and the average becomes 0.7 degrees. Since the outside is actually 0.23^{o}C cooler, the total change in radiant temperature is estimated to be 0.9^{o}C.

Turning now to the upper or northern portion of the sprayed side of the grid, a warm region is found in the three sets of data.

Examination of the in-situ temperature of the upper region of the wet portion of the grid indicates a poor correlation between the thermocouple readings and the radiometer readings. This is due to the presence of isolated patches of partially frozen water and the fact that the radiometer sensor was not necessarily aimed exactly at the spot where the thermocouple junction was imbedded. The temperature varied abruptly at the edge of a puddle of water and with the darkness on the roof an error of 10 to 15 cms. in aiming the radiometer was quite possible.

Several extra radiometer readings were taken in the vicinity of the puddles after the whole grid had been measured. It was found that the radiometer readings were very sensitive to the vertical angle. On close examination, this turned out to be a case of determining exactly what was in the field of view of the sensor. Readings taken over thin ice with no water underneath read -2^{o}C, -5^{o}C and -6^{o}C at three different spots. Readings over partially-frozen puddles taken either from above or at an angle were consistently in the range of 0 to +1^{o}C.

The variation in radiation temperature of the thin ice surfaces with no water underneath is attributed to various stages of cooling following freezing since there was known to be no temperature anomalies on the dry roof.

A radiant temperature of 0^{o}C at several of the partially-frozen areas is due to the presence of a water-ice interface just below the thin ice surface. None of the puddles were more than 1 cm. deep so the ice was thin. Since ice has a relatively high thermal conductivity and the water-ice interface is at or near 0^{o}C a thin layer over the interface will exhibit a surface temperature close to that of the interface below it under light-wind conditions such as are usually prevalent when aerial thermography is being taken. This aspect of the experiment on the control roof confirms what was postulated as a possibility in the report of the 1977 study, viz - a two-phase system of ice-over-shallow water on a roof exhibits a radiant temperature close to 0^oC until the system freezes completely to the ice phase. Following complete freezing the system cools towards the temperature of the surrounding dry roof surface.

Where regions with an apparent radiant temperature of 0^oC correlate with water in the daytime photographs they can be interpreted as having a low probability of heat loss. Such an interpretation is subject to verification by other means of course, but experience gained on this project and over the past year in P.E.I. shows that in the majority of cases wet areas exhibiting warm signatures are not trouble spots because in thermograms taken when the roof was drier the anomalies disappear.

4.4 Calculated Radiant Temperature

Brightness temperatures of partially-emitting, partially-reflecting, surfaces can be readily calculated using linear approximations when only small changes in temperature and radiant flux are involved.

Two basic equations are used:

$$e_b(\lambda) = \frac{2\pi hc^2}{\lambda^5(e^{hc_0/k\lambda T}-1)} \qquad (1)$$

where $e_b(\lambda)$ is the hemispherical spectral emissive power at wavelengh λ of a black body a temperature T, h is Planck's constant, k is Boltzman's constant, and c_o is the velocity of light in vacuum.

Integrating equation (1) for all λ and defining a new constant σ yields $e_b = \sigma T^4$ (2)

where e_b is the total hemispherical emissive power overall and σ is the Stefan-Boltzmann constant.

Equation (1) is the familiar Planck radiation law, equation (2) is the familiar Stefan-Boltzman law.

Using these two equations we can derive an equivalent brightness temperature for a surface that is both emitting and reflecting flux.

Assuming a surface at temperature T we calculate e_b from equation (2). e_b is then adjusted for emissivity ε to give the actual total emissive power $e_a = \varepsilon e_b$.

We define a radiant power deficit $\Delta e' = (e_b - e_a)$ which can be expressed as a temperature decrement by differentiating (2) and re-arranging terms:

$$\Delta T' = \frac{\Delta e'}{de/dT} = \frac{\Delta e'}{4\sigma T^3} \qquad (3)$$

$\Delta T'$ is the apparent lowering in temperature of a non-perfect emitter at temperature T and having emissivity ε.

We define $T_{eff} = T - \Delta T'$ as the effective black-body radiation temperature of the non-perfect emitter.

We then calculate the contribution of reflected sky radiation and use it to reduce $\Delta e'$ whence we arrive at Δe, the net radiation deficit. Substituting Δe in (3) yields ΔT from which we get $T_b = T - \Delta T$ where T_b is the brightness temperature defined in Section 2.

The infrared detectors used in the current study only measure over a portion of the spectrum and the power-versus-frequency curve differs for objects at different temperatures. Hence, a correction must be considered to match the flux from surfaces at different temperatures into the spectral band of interest. The engery in any band between λ_1 and λ_2 can be calculated from equation (1) or more conveniently from available tabulated data as found in, for example, Reference 2, Table A-4, Appendix A, page 739. Calculation of the appropriate scale factor for surfaces at temperatures of interest in the present study show that at $-8^{\circ}C$ and $-18^{\circ}C$, 32% and 30% respectively of the total emitted power e_b falls into the 8 to 14 micron band. These differences are not large and when the relative contribution of the reflected sky radiation - typically 10% of e_b - is considered the correction becomes second order and can safely be neglected.

Using the sample linear approximation developed above, we can evaluate the brightness temperature for surfaces studied in the present project. Two cases will be considered: a dry surface under a reflecting radiation from the sky and a wet (or frozen) surface at the same temperature as the dry surface and under the same sky. The temperatures used will be (nominally) the temperatures measured during the experiment.

In the calculations that follow the experimental value of σ given in Reference 2, page 738, is used. σ (experimental) = 5.729×10^{-12} watts $(cm)^{-2}$ $(^oK)^{-4}$. ^oK = degrees Kelvin.

CASE 1: DRY ROOF

Roof temperature = T(roof) = 265^oK

Radiant sky temperature = T(sky) = 255^oK

Emissivity of roof = ε(roof) = 0.9

Reflectivity of roof = R(roof) = (1-ε(roof)) = 0.1

e_b (roof) $=\sigma(T(roof))^4 = 282 \times .10^{-4}$ watts/cm^2

e_a (roof) $=\varepsilon(roof) e_b(roof) = 254 \times 10^{-4}$ watts/cm^2

$\Delta e'(roof) = (e_b - e_a) = 28 \times 10^{-4}$ watts/cm^2

With no compensating reflected radiation from the sky,

$\Delta T' = \Delta e'$ (roof)$/4\sigma$ $(T(roof))^3 = 6.6^oK$, a drop of almost 7^oC and $T_{eff} = 258^oK$ or -15^oC.

$e_b(sky) = \sigma(T(sky))^4 = 242 \times 10^{-4}$ watts/cm^2

Reflected sky radiation $\Delta e'_s = R(roof) e_b(sky) = 24.2 \times 10^{-4}$ watts/cm^2.

Net radiation deficit $\Delta e = \Delta e' - \Delta e'_s = 3.8 \times 10^{-4}$ watts/cm^2

The net radiant temperature deficit $\Delta T = \frac{\Delta e}{4\sigma(T(R))^3}$

$= 0.9^\circ K$ or $0.9^\circ C$,
a drop of approximately 1 degree Centigrade and,

T_b(dry roof) = $264^\circ K$ or $-9^\circ C$, to the nearest degree.

CASE 2: WET OR FROZEN ROOF

Actual temperature of wet surface T(wet)=$265^\circ K$ (Note 1).
Radiant Sky Temperature T(sky)=$255^\circ K$
Emissivity of wet (frozen) surface ε(wet)=0.98
Reflectivity of wet (frozen) surface R(wet)=0.02
Repeating the calculating as for Case 1 yields:

$$\Delta T' = 1.3^\circ C$$
$$\Delta T = 0.2^\circ C$$

For the case of side-by-side wet and dry surfaces therefore with dry surface at $-8^\circ C$ and the icy surface at $-8.2^\circ C$, to the nearest tenth of a degree, and a uniform sky temperature of $-18^\circ C$, we would expect the dry surface to have a brightness temperature of $-8.9^\circ C$ and the wet surface to have a brightness of $-8.4^\circ C$, a difference of 0.5 degrees. This calculated difference in the brightness temperature of the two surfaces is within $0.2^\circ C$ of the best estimate of the difference of $0.7^\circ C$ as observed on the aerial thermogram of the control

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NOTE 1: The wet side will actually be slightly cooler than the dry side due to higher emissivity but this will be taken into account later.

site. The variation between the two numbers is consistent with the accuracy of the data. The emissivity figures used in the foregoing calculations are averages based on figures found in a number of references for example Kreith (Ref. 3), Wolfe (Ref. 4) and Griggs (Ref. 5). In conversation with other workers in the field, the relatively high emissivity of water and ice used here might be questioned because of the danger of surface contamination by very thin oil films. Such films could conceivably be picked up on a tar and gravel roof and would have the effect of reducing the emissivity and hence lowering T_{eff} for the wet or icy surfaces.

In the example being studied here the brightness temperature of the frozen region of the grid was sufficiently different from the brightness temperature of the dry region to cause a constant change of one grey tone. In a case to be reported later in Section 5.10 there is an icy region on a roof that blends completely with the surrounding dry region on the roof. Two reasons can be given for the lack of a change in contrast in the second case. First, the radiant temperatures of the dry and frozen sections of the roof studied in 5.10 may be such that they both fit in one temperature-slice band. This is quite conceivable since the narrowest band used in the present sutdy is 0.66^{o}C. Second, the frozen region on the control grid may not have come to complete and final equilibrium in the two hours between the time the spraying was done and the aerial data was taken whereas the wet portion in 5.10 cooled down from sunset - a cooling time of some 6 to 7 hours depending upon when the spot in question fell under the shadow of another part of the building. In the examination of thermograms for other sites, examples similar to what was observed at the control site were found i.e. a small change of contrast occurs. The point being made here is that the quantitative data in the thermograms are in relatively large "quanta", a fact that must be borne in mind during the analysis.

The results of the experiment on the control roof and the calculations that support the experimental data provide two useful guides for future thermography work.

(i) The partial flooding procedure provides a sufficiently accurate indication of the net effect of sky radiation and emissivity of dry and wet surfaces to allow preparation of a proper temperature distribution map from an aerial thermogram.

(ii) Wet or frozen regions on a roof can be analysed into three categories:

1. A two-phase water-ice system at $0^{o}C$.
2. Solid ice at a (known) temperature between $0^{o}C$ and the temperature of the dry parts of the roof.
3. Solid ice (or an icy surface) at the same temperature as the dry roof.

	1	2	3	4	5	6	7	8	9
A	-7.8	-8.0	-7.6	-7.7	-8.0	-7.6	-8.0	-8.2	-6.6
B	-8.3	-8.2	-7.9	-8.5	-7.9	-8.6	-8.1	-7.9	-8.3
C	-8.4	-8.6	-8.3	-8.9	-8.8	-8.7	-8.6	-8.5	-8.6
D	-9.1	-8.8	-8.5	-8.6	-8.5	-8.4	-8.0	-8.7	-8.4
E	-8.6	-8.5	-8.5	-8.4	-8.3	-8.6	-7.8	-8.7	-8.6
F	-8.2	-7.9	-8.3	-8.1	-8.6	-8.9	-8.1	-8.5	-8.6
G	-8.2	-8.1	-8.0	-7.8	-8.8	-8.7	-7.9	-8.4	-8.5
H	-8.1	-8.1	-8.1	-8.1	-7.9	-8.2	-8.4	-8.2	-8.1
I	-8.2	-8.2	-8.1	-8.7	-8.7	-8.6	-8.5	-8.5	-8.2

FIG. 4.1: Thermocouple temperatures over dry grid two hours after dark, March 26, 1978. Temperatures in ^{o}C.

	1	2	3	4	5	6	7	8	9
A	-8.0	-8.0	-8.0	-8.0	-8.0	-8.0	-7.5	-7.5	-7.0
B	-6.8	-6.8	-6.5	-7.0	-7.0	-7.5	-7.3	-7.0	-7.0
C	-6.8	-6.8	-6.5	-6.8	-6.8	-6.5	-6.5	-6.3	-6.5
D	-6.5	-6.3	-6.3	-6.5	-6.5	-6.3	-6.0	-6.0	-6.0
E	-6.5	-6.0	-6.0	-6.0	-6.0	-6.0	-6.0	-6.0	-6.0
F	-5.9	-5.8	-5.8	-5.8	-6.1	-6.1	-5.9	-5.9	-6.0
G	-5.8	-5.6	-5.5	-5.5	-5.7	-5.7	-5.5	-5.5	-5.6
H	-5.5	-5.5	-5.5	-5.6	-5.5	-5.7	-5.5	-5.6	-5.6
I	-5.5	-5.4	-5.6	-5.6	-5.7	-5.7	-5.8	-5.8	-5.7

Figure 4.2: Radiation temperatures over dry grid two hours after dark, March 26, 1978. Readings are in ^{o}C.

	1	2	3	4	5	6	7	8	9
A	-8.2	-8.3	-7.9	-7.9	-8.2	-3.6	-3.7	-8.0	-2.3
B	-8.2	-8.1	-7.8	-8.3	-8.1	-6.2	-1.5	-2.6	-6.6
C	-7.9	-8.0	-7.9	-8.3	-8.3	-8.2	-5.9	-4.0	-4.2
D	-8.2	-8.1	-7.9	-8.0	-8.2	-7.7	-7.2	-7.7	-0.5
E	-7.8	-7.6	-7.7	-7.7	-7.8	-8.2	-7.9	-7.9	-0.7
F	-7.8	-7.4	-7.9	-7.7	-8.0	-8.7	-7.9	-8.3	-8.1
G	-7.7	-7.5	-7.5	-7.3	-8.0	-8.4	-7.8	-7.8	-7.6
H	-7.4	-7.4	-7.5	-7.6	-7.5	-8.2	-8.0	-7.8	-7.9
I	-7.7	-7.6	-7.5	-7.7	-7.7	-8.4	-8.3	-8.2	-7.6

DRY WET

Figure 4.3: Thermocouple temperatures over partially-sprayed grid, 11:15 P.M., March 26, 1978. Readings are in ^{o}C.

	1	2	3	4	5	6	7	8	9
A	-6.7	-6.6	-6.5	-6.5	-6.6	-4.0	-4.0	-6.0	-4.8
B	-6.0	-6.0	-6.0	-6.0	-6.0	-3.0	-2.0	-2.0	-4.0
C	-6.0	-6.0	-5.5	-6.0	-6.2	-5.0	0.0	+1.0	+1.0
D	-5.5	-5.5	-5.4	-5.5	-6.0	-5.0	-5.0	-1.0	+1.0
E	-5.5	-5.5	-5.6	-5.6	-6.0	-6.0	-6.0	-5.0	+1.5
F	-5.5	-5.5	-5.5	-5.5	-5.5	-5.5	-5.5	-5.5	-5.0
G	-5.5	-5.5	-5.5	-5.6	-5.8	-5.8	-5.6	-5.1	-5.0
H	-5.1	-5.3	-5.4	-5.5	-5.5	-5.7	-5.5	-5.5	-5.5
I	-5.4	-5.2	-5.3	-5.5	-5.5	-6.0	-5.9	-5.6	-5.5

DRY WET

Figure 4.4: Radiation temperatures over partially-sprayed grid, 11:25 P.M., March 26, 1978. Readings are in ^{o}C.

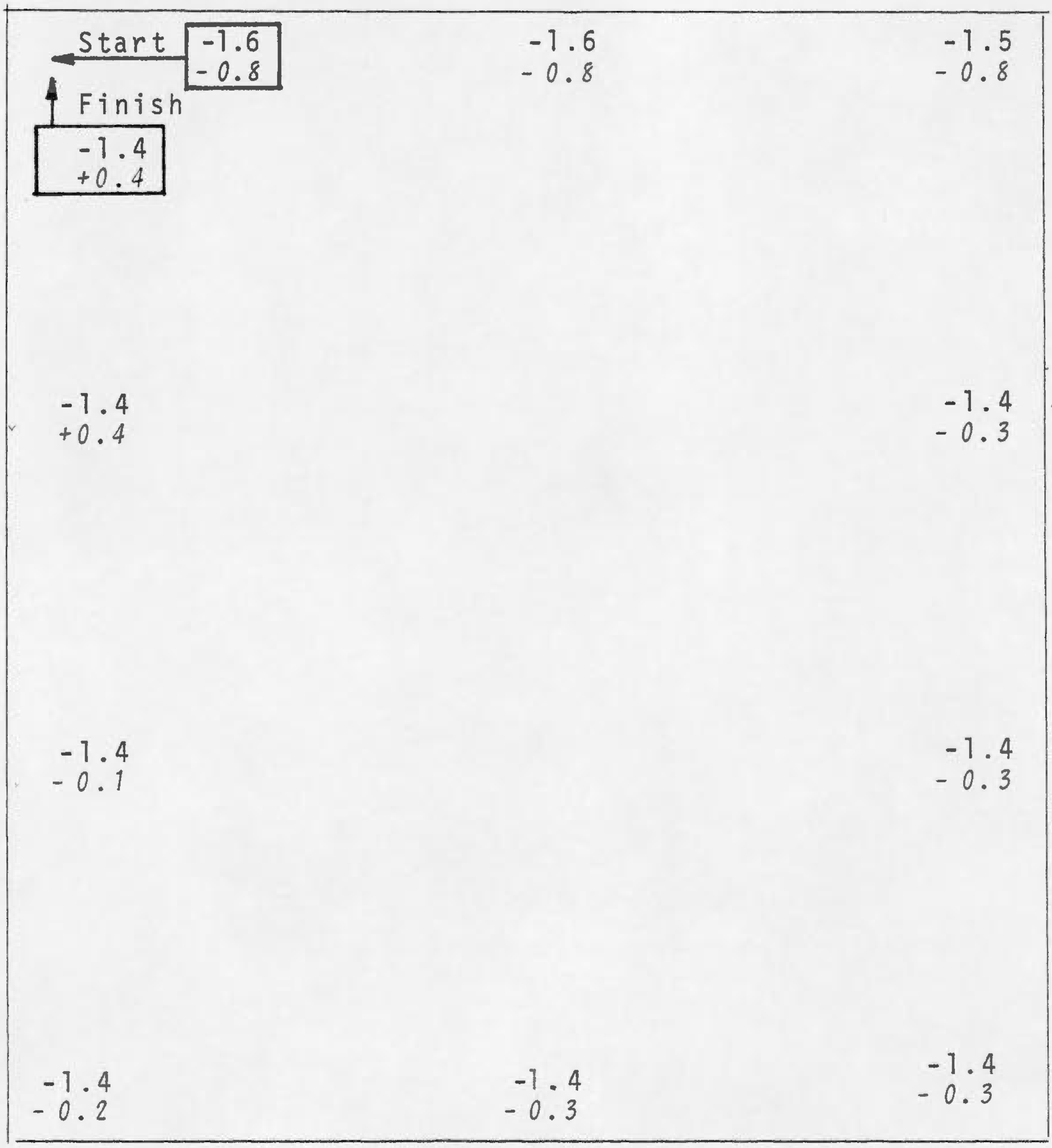
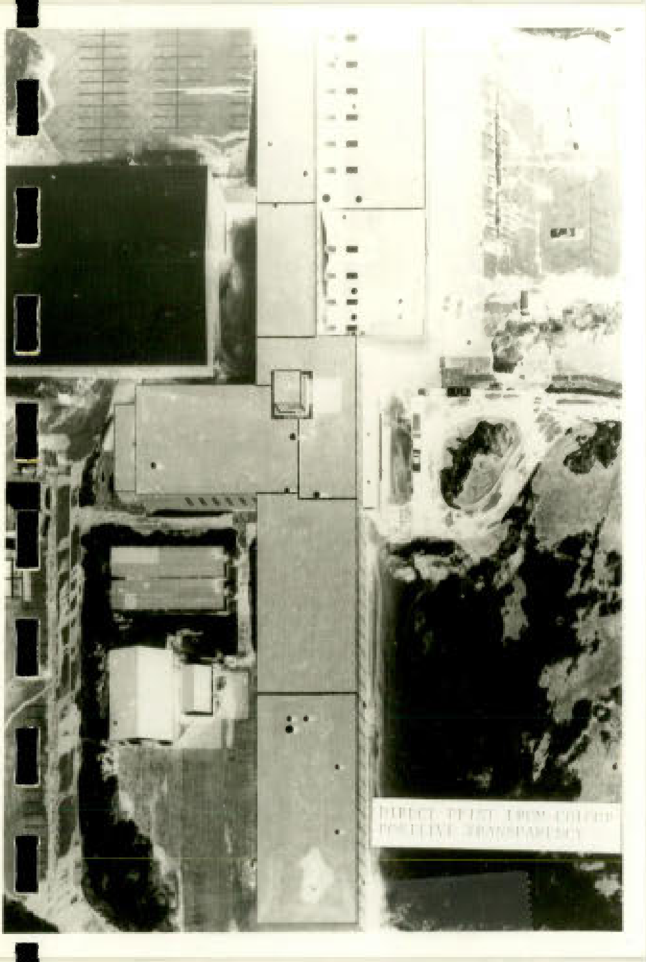


Fig. 4.5 SURFACE TEMPERATURES OF THE RECTANGULAR POOL, 11:15 P.M., March 26, 1978. TEMPERATURES IN ^{o}C.

UPPER NUMBER: THERMOCOUPLE TEMPERATURES
LOWER NUMBER: PRT-5 RADIOMETER TEMPERATURES


26/3/78


DIRECT PRINT FROM COLOUR
POSITIVE TRANSPARENCY

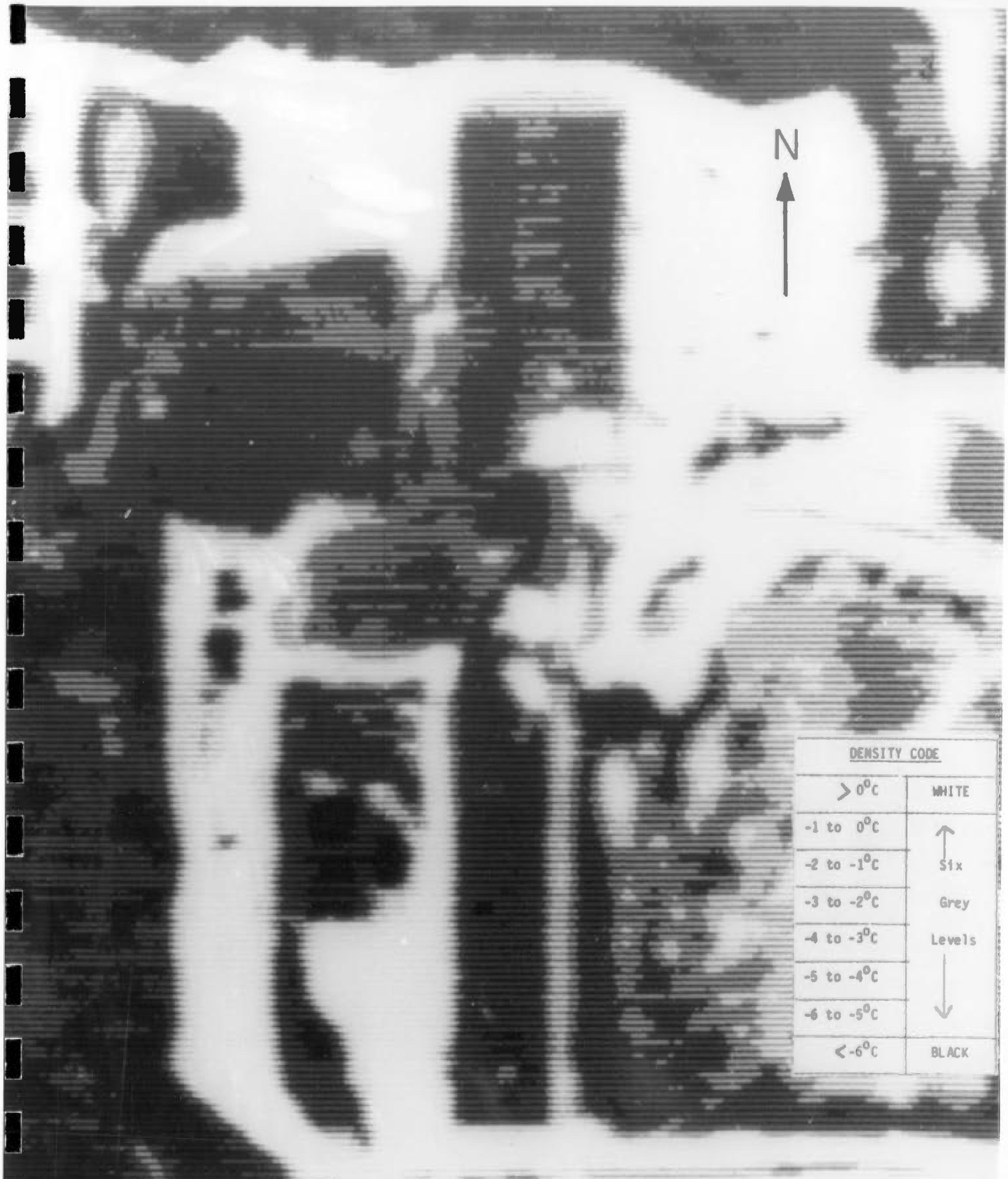


FIG. 4.6: Hollard College Royalty Centre, 11:10 P.M., March 26, 1978. Air temperature, -8.4°C. Wind, 10 kph approximately. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.

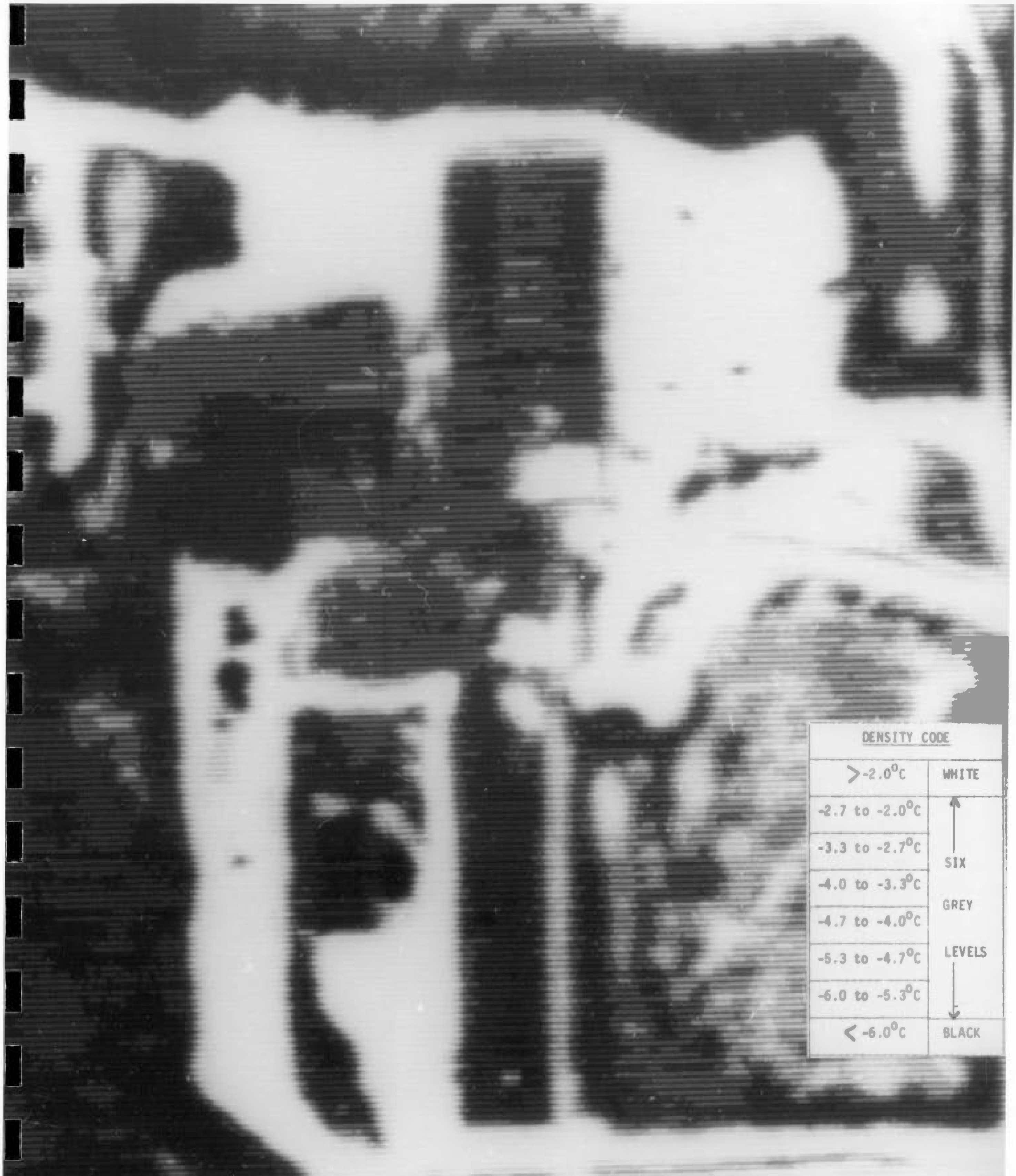


FIG. 4.7: Holland College Royalty Centre, 11:00 P.M., March 26, 1978. Air temperature, -8.4°C. Wind, 10 kph approximately. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.

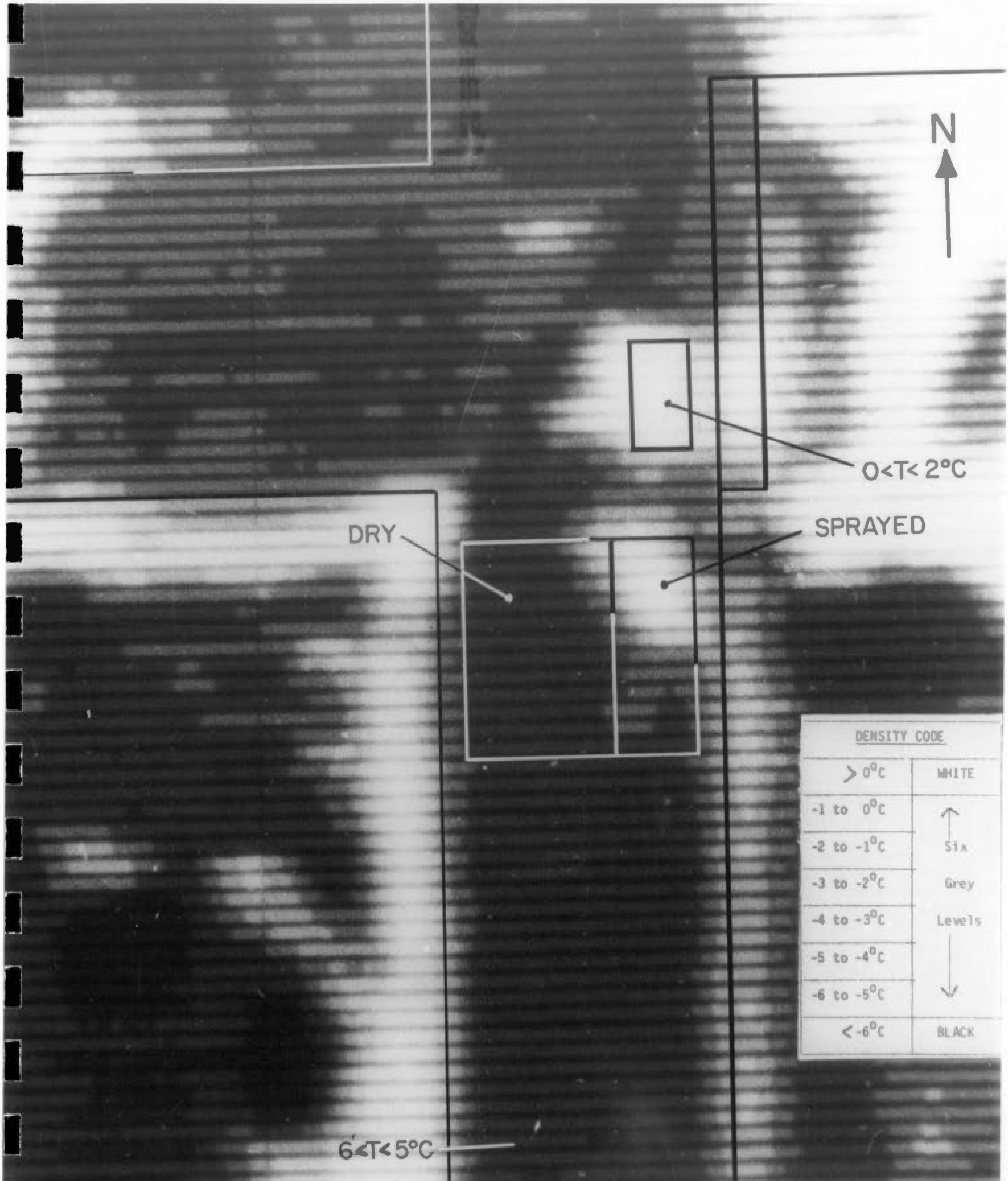


FIG. 4.8: Holland College Royalty Centre, 11:00 P.M., March 26, 1978. Air temperature, -8.4°C. Wind, 10 kph approximately. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.

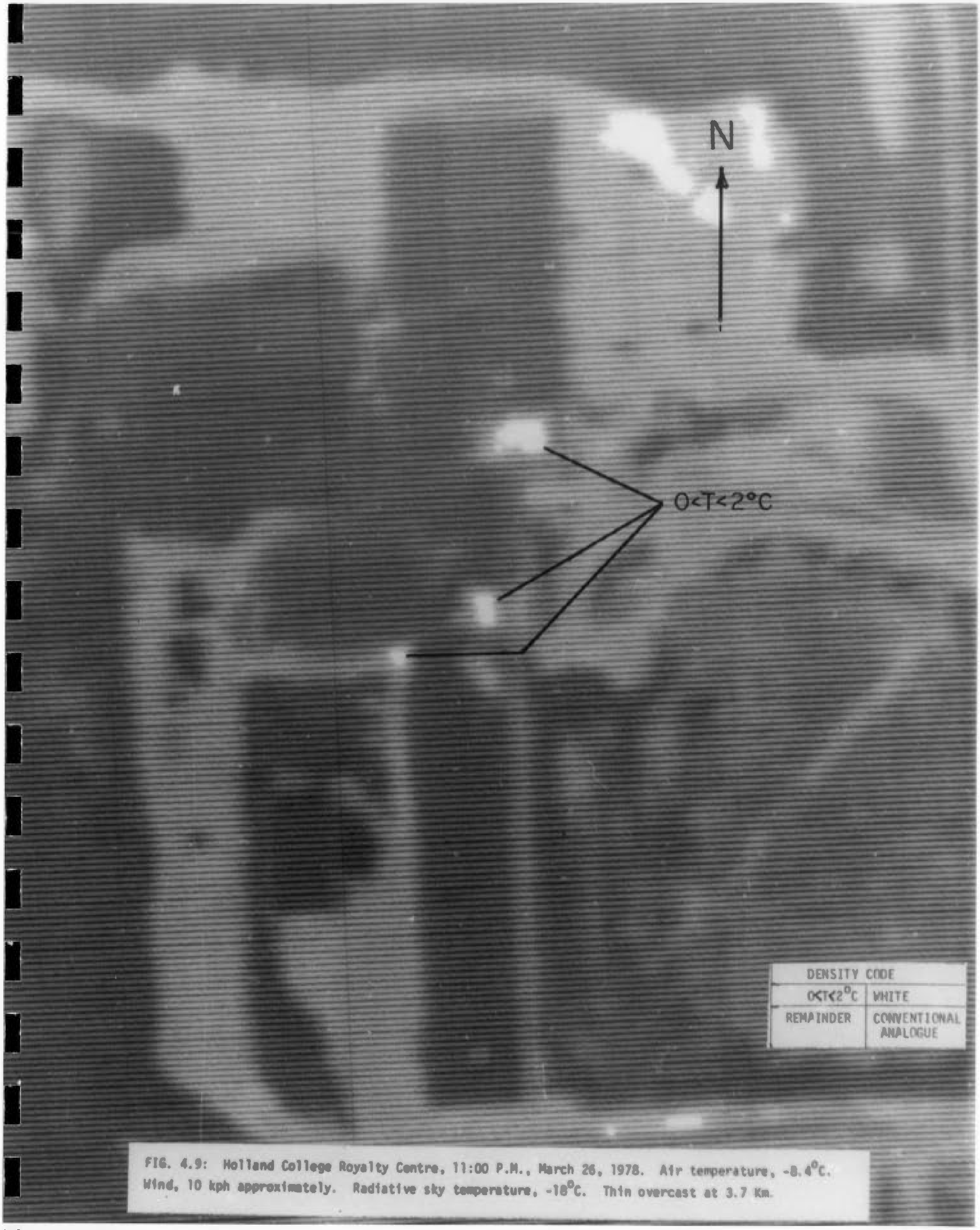


FIG. 4.9: Holland College Royalty Centre, 11:00 P.M., March 26, 1978. Air temperature, -8.4°C. Wind, 10 kph approximately. Radiative sky temperature, -18°C. Thin overcast at 3.7 Km.

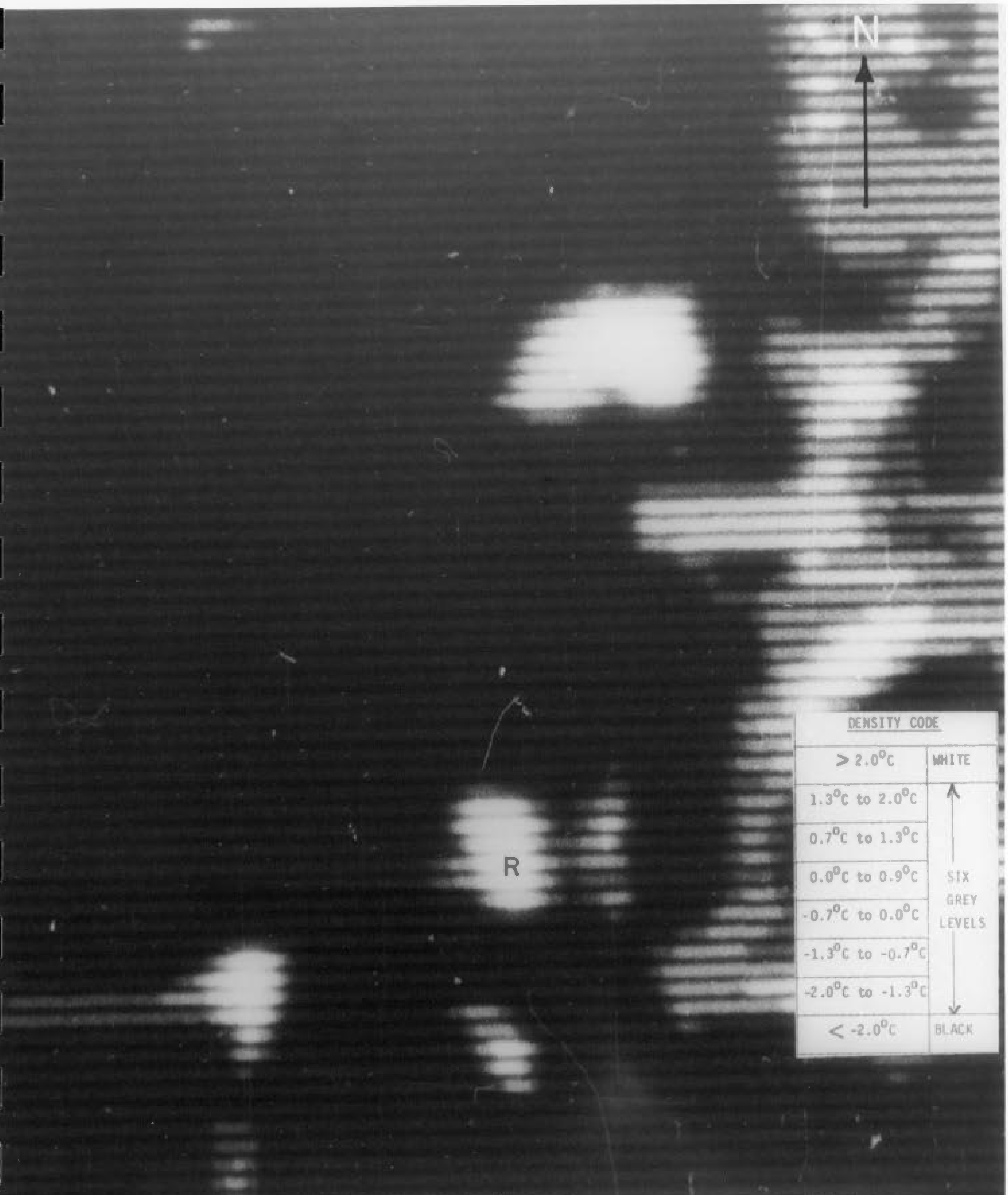


FIG. 4.10: Holland College Royalty Centre, 11:00 P.M., March 26, 1978. Air temperature, -8.4°C. Wind, 10 kph approximately. Radiative sky temperature, -18°C. Thin overcast at 3.7 km.

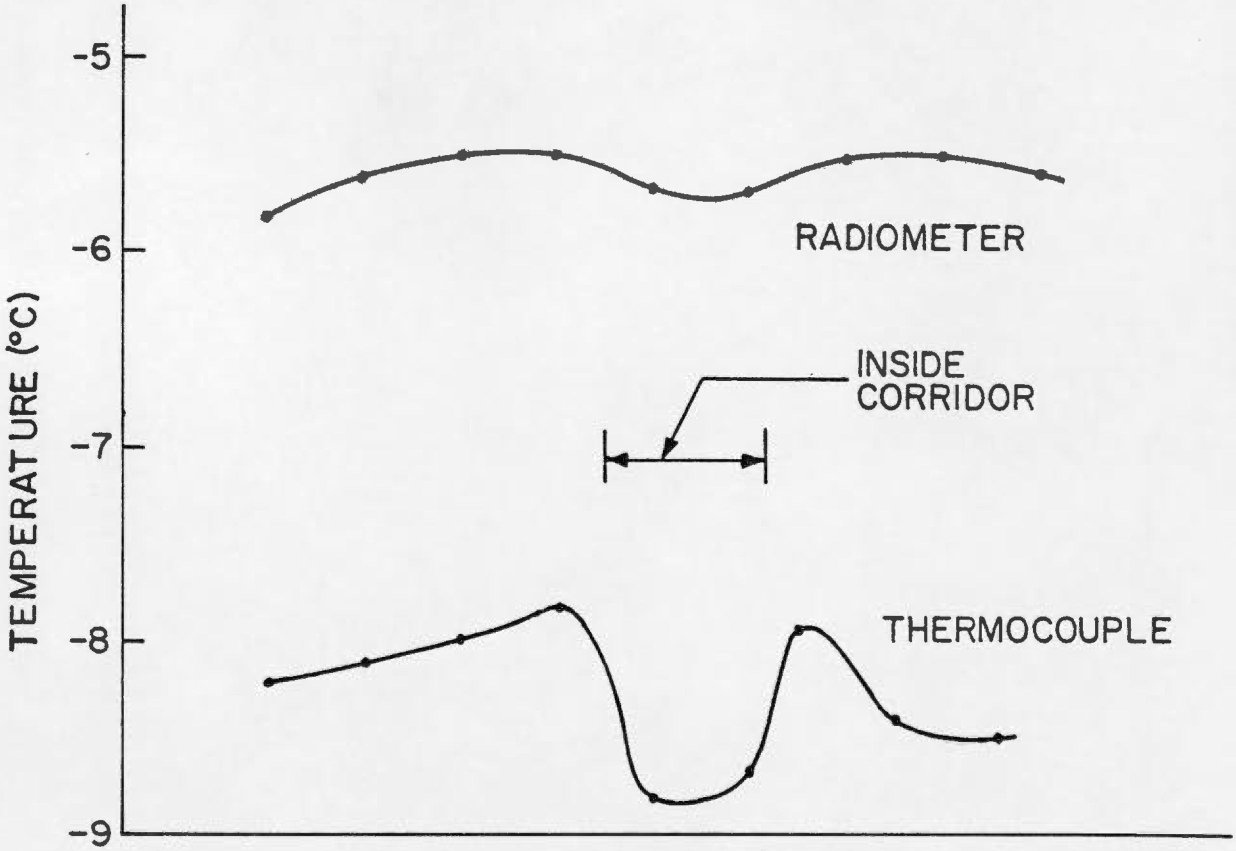


FIG. 4·11 TEMPERATURE PROFILE OF ROW "G" OF CONTROL GRID, 8:30 P.M., MARCH 26, 1978.

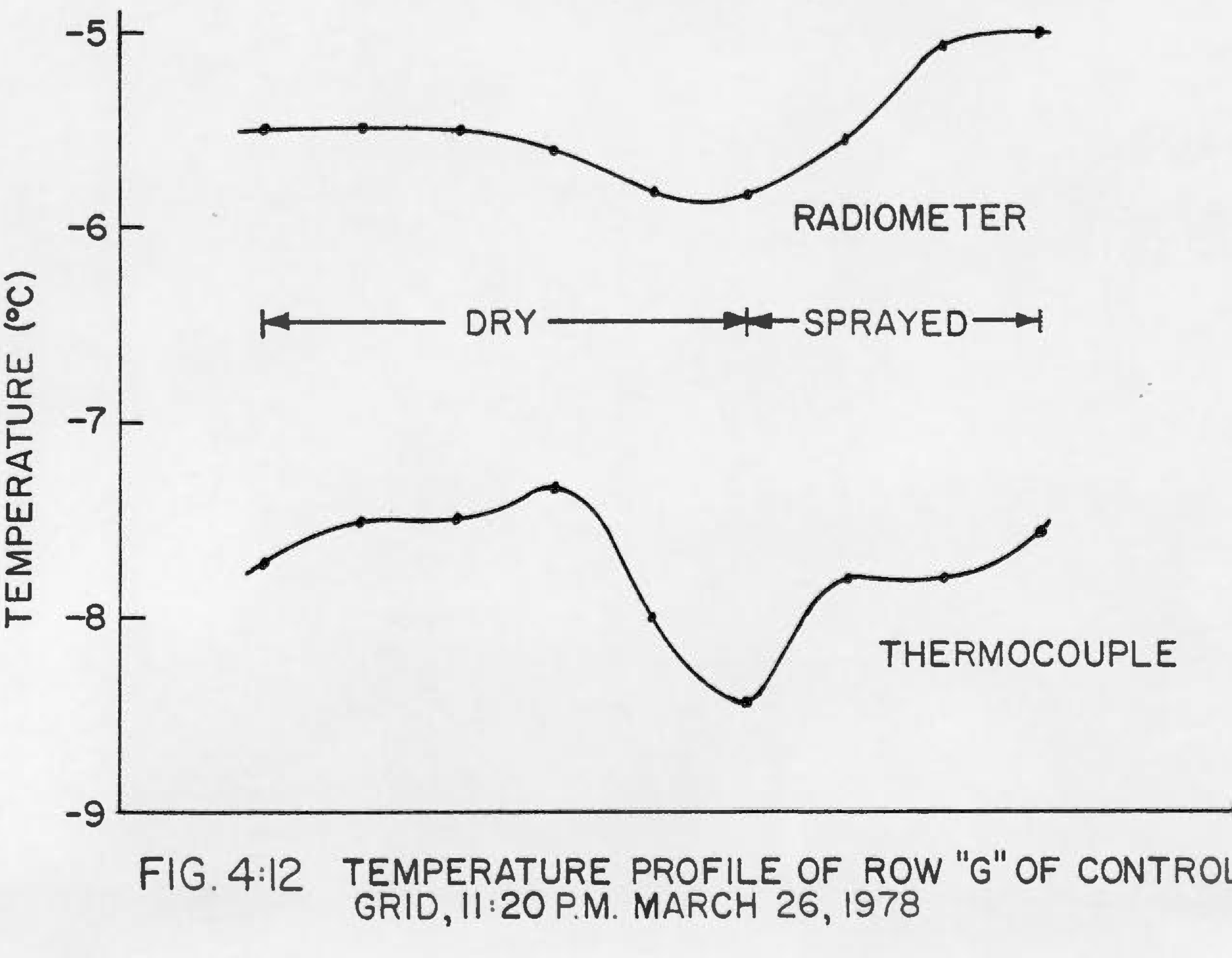


FIG. 4·12 TEMPERATURE PROFILE OF ROW "G" OF CONTROL GRID, 11:20 P.M. MARCH 26, 1978

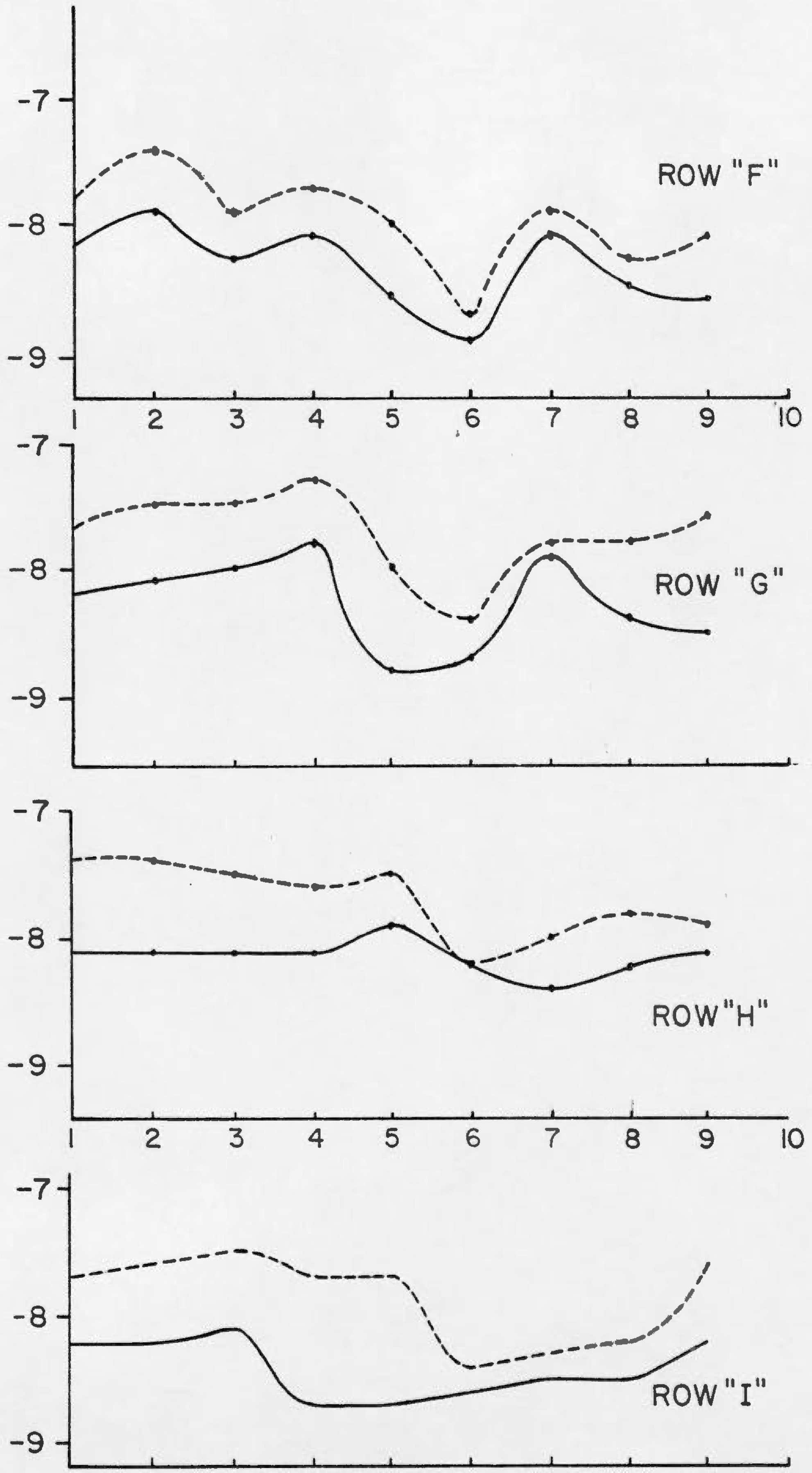


FIG. 4:13 THERMOCOUPLE TEMPERATURES (°C)
ROWS F, G, H & I
——— = 8:30 P.M. READINGS
- - - - = 11:20 P.M. READINGS

5. Analysis of 1977 and 1978 Thermographs

5.1 Background

In this section a comparative analysis of thermographs for 1977 and 1978 is presented for 10 sites in Charlottetown.

They are:

5.4	P.E.I. Government Buildings
5.5	Holland College, Main Building
5.6	Holland College, Students Residence
5.7	Robertson Library, University of P.E.I.
5.8	Dairy Processing Plant
5.9	Commercial Store - Mall
5.10	Heavy Machinery Depot
5.11	Birchwood Junior High School
5.12	Confederation Center
5.13	Charlottetown Hospital

As in 1977, interpretation was done visually using analogue and level-sliced thermograms, air photos, and local information on building design and building use.

Eight of the ten sites were visited by a two-man team to verify the interpretation which was done first. The main buildings and the student residence at Holland College were not visited. In addition to the post-interpretation visits, the heavy machinery depot and the P.E.I. government buildings were visited within a day to two of the day the remote-sensing flights was made.

A comparative examination serves two purposes. First, it permits the original interpretation to be either confirmed or adjusted based on different conditions of ice, water and snow cover. Second, it provides an assessment of the relative difficulty of interpreting thermograms with and without sufficient quantitative emissivity data to derive reliable temperature profiles. No quantitative emissivity data was available in 1977.

The information gained from the wet/frozen/dry test surfaces on the control roof contributed to the interpretation of the other Charlottetown sites in the following way:

1. The allowance to be made for the emissivity difference between a dry surface and a wet (or frozen) surface which are both at the same temperature is $1/2^{o}C$, with the dry surface being the cooler of the two. Any remaining contrast change on the thermogram that corresponds to a wet region in the air photo represents a real difference in temperature.

2. Surfaces in the thermogram that are at approximately $0^{o}C$ and relate to water in the air photo are interpreted as two-phase water-ice systems.

For an interpreter this was a very significant improvement over the 1977 situation in that it removed the basic dilemma of not knowing whether or not increases in brightness at a wet area were due to changes of temperature, or changes of emissivity or some combination of both. An explicit assessment of heat loss was not possible in many instances where there was water on a roof, however, because there appears to have been insufficient time for the water which had melted during the day to freeze and come to thermal equilibrium with the surrounding dry sections of the roof and the ambient air. This factor then becomes the limiting element in a heat-loss analysis. There is no straightforward procedure which will establish that a wet spot that is warmer than the surrounding area is at final equilibrium with the environment and is being kept warmer by heat flow from below or is in the process of cooling but its fall in temperature is lagging behind that of the dry sections because of its additional heat capacity.

5.2 General Observations

The majority of flat roofs were significantly dryer and free of snow in 1978 than they were in 1977. With the improved dryness and less snow cover, the interpretation of the 1978 data was more straightforward and, hence, contains fewer doubtful instances. This allowed a significant number of ambiguous situations in 1977 to be resolved in favour of a more definite interpretation.

A second feature that distinguishes the two data sets is the relative warmness of the bare ground and pavement in 1978. There is a two-fold reason for this change. First, the 1977 data was taken much earlier in the year - March 2, 1977 vs. March 26, 1978. With more retained frost in the ground, solar heating would not be as effective in raising the surface temperature gradient from the surface downward. Second, 1978 was exceptional in that there was very little frost penetration, even at the peak of the cold season, according to local knowledge.

The availability of reliable temperature profiles over wet and dry areas for 1978, based on the proper allowance for variations in emittance and sky temperature, and the knowledge that shallow puddles exhibit a surface temperature of $0^{o}C$ until all of the water (not just the surface layer) has frozen, eased the task of interpreting the signatures for the majority of wet areas. The net effect of having this improved background of knowledge was to assign a higher proportion of "warm", wet areas to the "wet-but-probably-satisfactory" category.

An examination and comparison of the general radiation temperature of roofs in the 1977 and the 1978 thermograms indicates that the "rise-above ambient" of the roofs in 1978 was greater than it was in 1977. The 1977 ambient air temperature was approximately $-5.5^{o}C$ at the test site and at the airport and the thermograms for the roof at the test site and a number of other roofs exhibited radiation temperatures in the range $-5.5^{o}C$ to $-6.5^{o}C$. By contrast, in 1978 the air temperature at the test site and at the airport was approximately $-8.5^{o}C$ and steady when the thermography was taken but for a large number of roofs, including the roof of the test site, the radiant temperature in the thermogram is in the $-6^{o}C$ range, a rise of about 2 $1/2^{o}$ above ambient.

Further evidence of this general difference in the data for the two years was uncovered by comparing the apparent radiant temperature of clean, isolated snow surfaces. Snow, having a high emissivity and hence a low reflectivity, should exhibit a net apparent radiant temperature that is close to but just slightly less than, the physical temperature of its surface. Because of low reflectivity the effect of reflected sky radiation will be slight unless the sky temperature was higher than the snow temperature. If the snow is in an open areas its surface temperature should be approximately the same as the average air temperature, within $\pm$ $1^{o}C$, say.

Therefore, snow lying in open areas and free of radiation exchange with nearby buildings, can serve as a useful "calibration" surface for relating the apparent radiant temperatures, as produced by the scanner and its ground processor to the most probable physical temperature of the same (high-emissivity) surface.

Comparison of isolated, clean, snow surfaces in 1977 and 1978 confirmed that the 1978 thermograms were in the order of 2 to 2 $1/2^{o}C$ "warmer" than the assumed temperatures of the surface.

In late 1977, after the 1977 project had been completed, a major field modification was made to the Daedulus ground processor at CCRS as a result of which the output thermogram negatives, from which working thermogram prints are made, were significantly improved both with respect to density range and target definition. Some features which were either blurred or lacking in contrast in the 1977 data set were seen more clearly when the 1977 thermographs were reproduced for the present report. Figure 5.1 is a print produced for the 1977 project. It can be compared to Figure 5.2, the same level-sliced thermograph but printed from an improved negative.

Cross-comparison of the temperatures of the roofs of buildings at different sites cannot be taken too far, because of variations in interior usage, temperature and air-flow. Nevertheless general observations are useful as a guide in assessing the overall performance of a roof from the point of view of heat loss.

For example, the overall thermal performance of the roof of the main building of the Holland College, Figure 5.5.1, the west wing of the Holland College Students Residence, Figure 5.6.1, and building C of the provincial building, Figure 5.4.1 are very similar in thermal expression. In all three cases the roof temperaure shows a trend to "straddle" the first and second grey levels while the temperature of some of the surrounding terrain is in the uncalibrated "black" region. On the other hand roofs

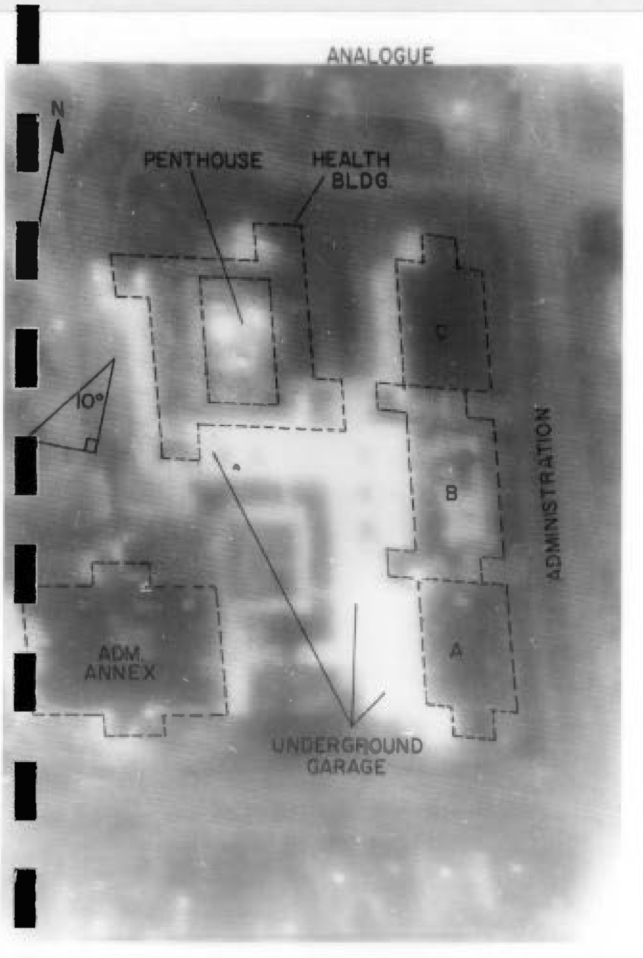


FIGURE 5.1: ANALOGUE THERMOGRAM OF P.E.I. GOVERNMENT BLDGS. IN 1977 REPORT.

FIGURE 5.2: SAME SIGNALS AS USED FOR FIGURE 5.1 BUT WITH SUPERIOR PROCESSING.

A and N of the provincial buildings, Figure 5.4.1, roof E of the penthouse at the dairy plant, Figure 5.8.1, and the dry section of the roof of the commercial store-mall, Figure 5.9.1 all exhibit surface temperatures in the uncalibrated "black" band or in the first grey level. The "rise-above ambient" is therefore quite noticeable for the first group and much less pronounced for the second group. Speaking generally, the roofs in the second group are definitely giving a superiour thermal performance over those in the first group.

5.3 Individual Comparative Analysis

The following sections contain the site-by-site comparative analysis of the roofs at ten sites. All level-sliced thermograms have been reproduced with the calibration table for the grey scale included. It must be noted that all eight levels - black and white plus six calibrated grey levels - are not necessarily present in any particular thermogram. If the dynamic range of the analogue signal from the scanner is sufficiently wide to cover the range of signals established by the particular set of temperature "slices" all bands will be present but the converse is also true.

5.4 P.E.I. Government Buildings

Thermograms for 1978 and 1979 are shown in Figures 5.4.1 and 5.4.2. The large slant angle to the scanner has caused a very pronounced edge effect E on the 1978 data.

There are noticeable differences in the data for the two years at 3 locations - roof H of the Provincial Health Building, roof B of the Administration Building and the parking lot.

Roof H:

The 1977 thermogram for roof H exhibits a much warmer thermal signature than do roofs N on the Administration Annex or roofs A and C. The difference is considerably enhanced with the improved reproduction of the 1977 data. A warm strip 1 on the west side of the roof was noted in 1977 and was subsequently correlated with a large interior suspended heating duct. The 1978 thermal signature for this building indicates a thermal performance that compares well with roofs A,B,C and N. The warm strip over the corridor is also missing or at least insignificant enough to escape detection with the level-slicing used, thus indicating an improved thermal performance of the roof.

During the visit to the building in May 1978, it was learned that roof H has been replaced in late 1977. The old roof was badly damaged by water penetration. Information on the design of the old roof was sketchy but it is believed to have been constructed with up to 10cm. of Foamglass insulation, a unicellular form of glass slab insulation. The building superintendent stated that when the insulation was removed it gave off a strong odor of "rotten eggs". On removal, the insulation ws found to be "pretty well saturated" with water indicating extensive breakdown of the outer membrane. The presence of large volumes of water under the membrane would explain the apparent high effective thermal conductivity of the roof in 1977.

With a better thermal performance over the expanse of the roof, the roof surface temperature is closer to the ambient air temperature in 1978 and other features such as 2, the (elongated) thermal signature of the stack are readily discerned. Warm air exhaust ports are located at 3, on the main roof deck and at 4 on top of the penthouse. P1 is a photo of the exhaust port at 3. There is a large plexiglass skylight south of vent 3 but it is obscurred in the "shadow" of the stack 2.
P2 and P3 are close ups of a patch of snow and an experimental solar collector situated on the south west region of the roof. Because of this snow, the foot of the penthouse wall appears to be slightly curved instead of following the line W.

Roof B:

In 1977, the thermogram was believed to be very warm. Although the actual temperature variations could not be worked out because of too many unknown quantities, from local knowledge and observation of the condition of the surface of the roof excess heat loss was suspected. Under the drier conditions of 1978, the roof compares favourably with the others, ruling out the possibility of extensive water damage although it was confirmed in 1978 that water leakage to the interior is still a problem.

The warm spot at 5 in the 1978 data coincides with surface water. It is already frozen in the thermograph because the indicated temperature is in the range -2 to -4^{o}C and is interpreted as being still cooling towards the ambient temperature. P4 was taken about 3 weeks later and shows ice and water lying in the same place but not as widespread as it was six weeks earlier. The same effect is presumed to be the cause of warm spots 6 on the 1977 print. Here again possible incipient problems were noted but under drier conditions the uncertainty can be resolved in favour of standing water or water and ice that is not yet in stable equilibrium with the ambient air.

Without attempting to quantify the difference, it can be seen that thermal performance of roofs B and C both of which are about 14 years old is inferior to that of Roof N which is about 5 years old and roofs A and H both of which are relatively new.

All thermostats in these buildings have been lowered by 2 centigrade degrees since 1977.

The local building superintendent was unable to offer any reason for a tendency for roofs B and C to be cooler on the east side. The prevailing wind was from the east at the time the thermography was taken but it is a doubtful correlation in view of a number of other tall buildings in the vicinity which would break up the air flow.

Parking Lot:

In 1977, the thermography was taken on a regular business day and the parking lot was filled with cars during the day, shielding the asphalt from the sun. Four hours after sunset, the warm and cool strips are still clearly visible. In 1978, the thermography was taken on Easter Sunday, occupancy in the parking lot was virtually nil, and the surface was uniformly heated with the possible exception of two spots which coincide with parked cars in the air photo.

Comparison of the data for roof B for 1977 and 1978 is an object leason to the effect that caution must be exercised in interpreted a "warm" infrared signature that coincides with standing water. Unless there is other evidence present, the warmer signature at the wet (or frozen) location is more likely to be due to differential cooling between the wet and dry surfaces (because of different thermal capacities) than it is to anomalous heat loss.

The most striking feature of the thermograms for this site is the ease which an upgraded roof can be spotted in an aerial thermogram.

P-1: MAR. 27,1978


P-2: MAR. 27, 1978


P-3: MAR. 27, 1978


P-4 MAY 4, 1978.

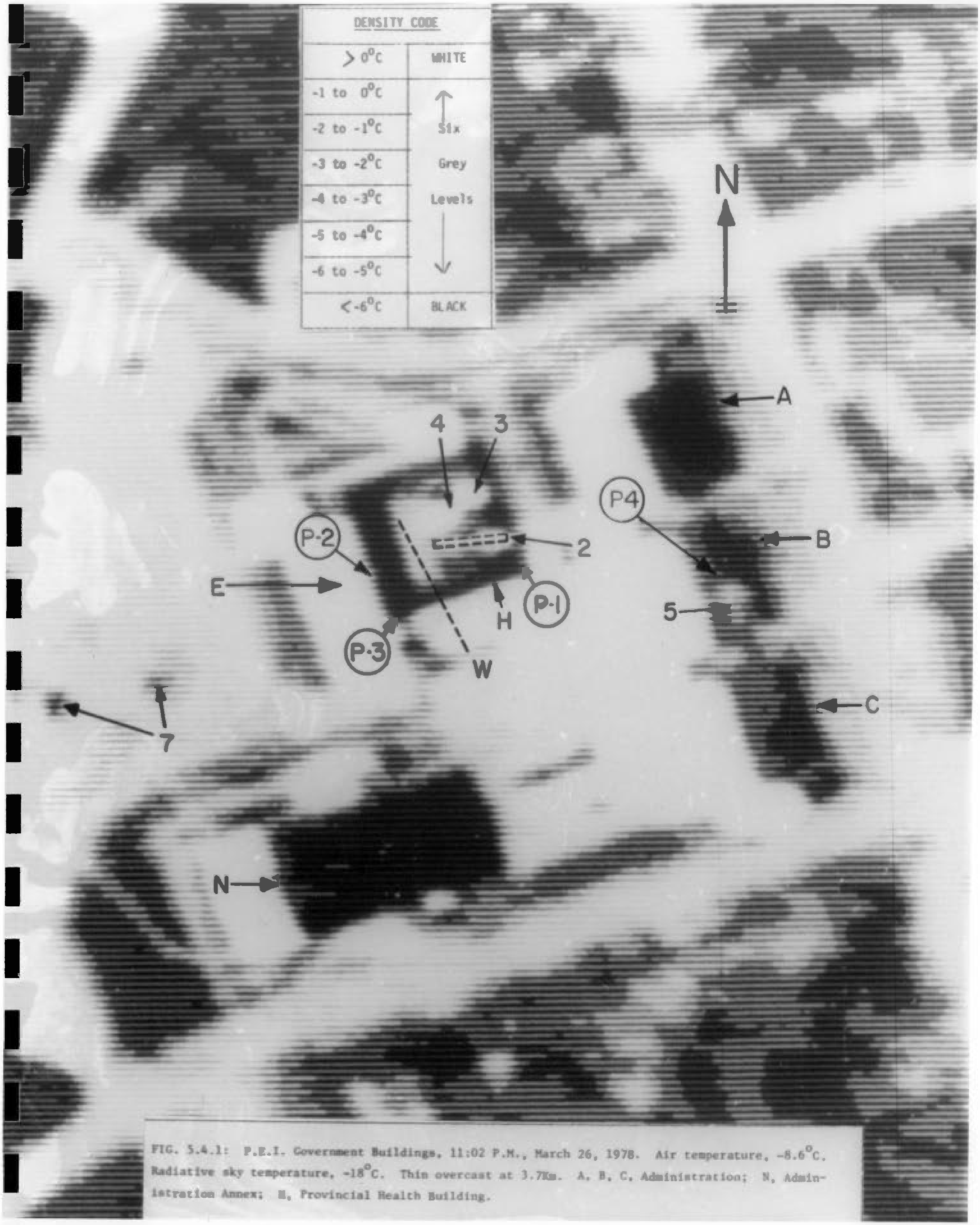


FIG. 5.4.1: P.E.I. Government Buildings, 11:02 P.M., March 26, 1978. Air temperature, $-8.6^{\circ}C$. Radiative sky temperature, $-18^{\circ}C$. Thin overcast at 3.7Km. A, B, C, Administration; N, Administration Annex; H, Provincial Health Building.

FIG. 5.4.2: P.E.I. Government Buildings, 9:08 P.M., March 2, 1977. Air temperature, -5.5°C. 50% scattered cloud at 0.9Km, 30% broken cloud at 3Km. A, B, C, Administration; N, Administration Annex; H, Provincial Health Building.

5.5 Holland College Main Buildings

Thermograms for 1978 and 1977 and an air photo for 1978 can be found in Figures 5.5.1 and 5.5.2.

This roof was only slightly drier in 1978 than in 1977. There was a significant number of wet areas. This is believed to be caused by a poor drainage system.

Ventilators 1 on the gymnasium are readily distinguishable in 1978 as they were in 1977.

In 1977 and 1978 the roof of wing SE of the college is, overall, cooler than the remainder of the roofs. The building superintendent was able to provide the following information which supports the relative coldness of the roof of this wing:

1. The roof was rebuilt four years ago.

2. The plumbing and heating in this wing is old and inefficient and the occupants complain continually about the cold.

3. The rooms are drafty, some windows cannot be completely closed.

The wing is used for construction technology and electronics instruction rooms.

Warm spot 2 on the 1978 thermograph coincides with a large puddle of water in the air photo and is interpreted as an incompletely frozen water/ice mixture. A slightly cooler ring about 2 is the outer edge of the puddle completely frozen but not yet at equilibrium with the ambient temperature.

Warm area 3 also coincides with water in the day photo. A surrounding damp area, part of which appears in the thermogram, can be seen in the day photo. The area in the photo is larger however so the outer region must have stabilized to the temperature of the roof when the thermogram was taken.

4 is a ventilator.

The north wing N appears to be generally wet throughout. Areas 5 and 6 definitely coincide with standing water surrounded by damp areas.

7 coincides with a ventilator but is much warmer in 1978 than in 1977. There is also a sort of chimney stack near the ventilator which may have been operative in 1978 and not in 1977. Area 8 has water in the day photo but is completely in the ice phase and presumably cooling to the ambient temperature.

The roof at 9 is a uniform temperature although part of it is wet or damp in the air photo. This is a good example of surface water that is shallow enough to freeze completely and come to equilibrium quickly with the surrounding dry surface with the result that there is no significant change in contrast between the frozen and the dry surface under the existing sky conditions.

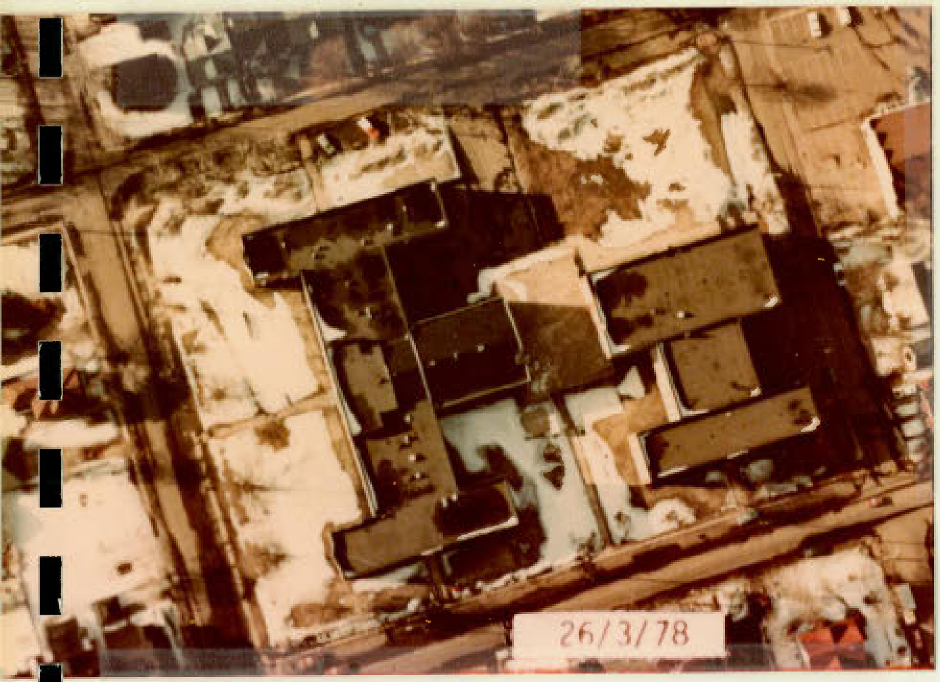

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FIG. 5.5.1: Holland College Main Building, 11:24 P.M., March 26, 1978. Air temperature, -8.6°C. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.

FIG. 5.5.2: **Holland College Main Building**, 9:24 P.M., March 3, 1977. Air temperature, $-5.5^{\circ}C$. 50% scattered cloud at 0.9Km, 30% broken cloud at 3Km.

5.6 Holland College Student Residence

Thermograms for 1978 and 1977 can be found in Figures 5.6.1 and 5.6.2. The residence consists of two wings several stories high connected by a single story lobby.

This roof is well drained and dry so that any anomalous heat-loss would be readily identifiable. The building is relatively new, 12 years.

Thermograms for 1977 and 1978 are similar, neither one indicates any warm regions that might indicate excessive heat loss. In a general way, the west wing W, runs slightly warmer overall than the east wing E, but the differences are not large. The thermogram for the west wing indicates that the temperature is close to the cross-over point in the digitizing circuits in the Daldulus ground processor in view of the fact that the thermal pattern changes in an irregular manner between two adjacent temperature bands. There is a tendency for the western half of the western wing to be warmer since it is more consistently in the higher of the two temperature ranges. The subtle change in temperature from east to west on this roof cannot be related to interior usage except in a global way. This is to be compared to examples of well-defined warmer areas, viz - the roof of the dairy plant (location 3) and the Charlottetown hospital (location 1) where a definite geometric outline is quite visible in the thermogram and can be related to interior usage.

The heat from an exhaust ventilator is readily observed in the thermographs for both years. The ventilation in this building is very well regulated since there are no bright spots from the numerous vents on the roof.

In the 1977 thermogram the roof over the lobby L appeared to be slightly warmer than the roofs of the two main wings. This feature is not observable in the 1978 data. In 1978 the doorway D, is more clearly delineated.


26/3/78

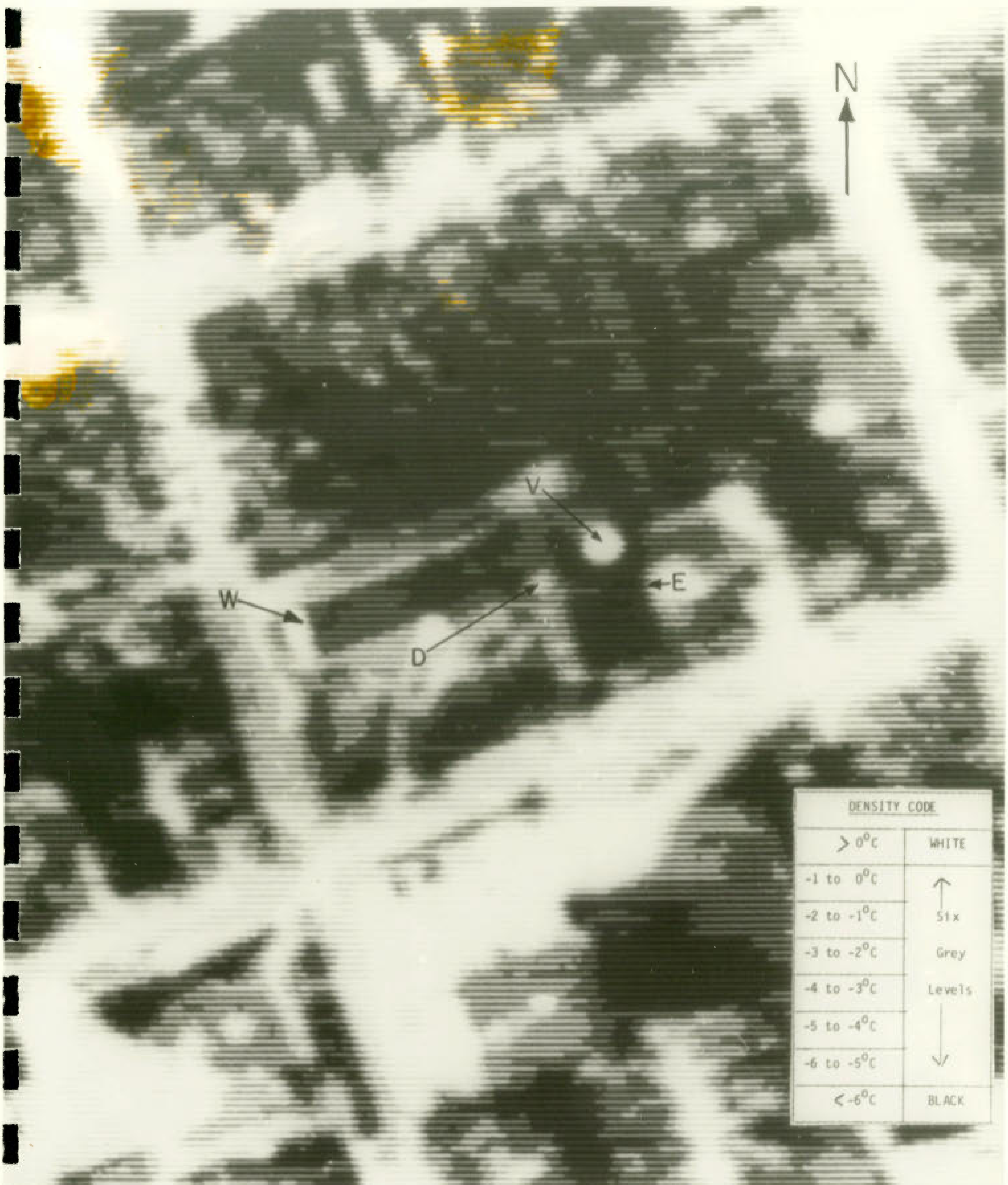
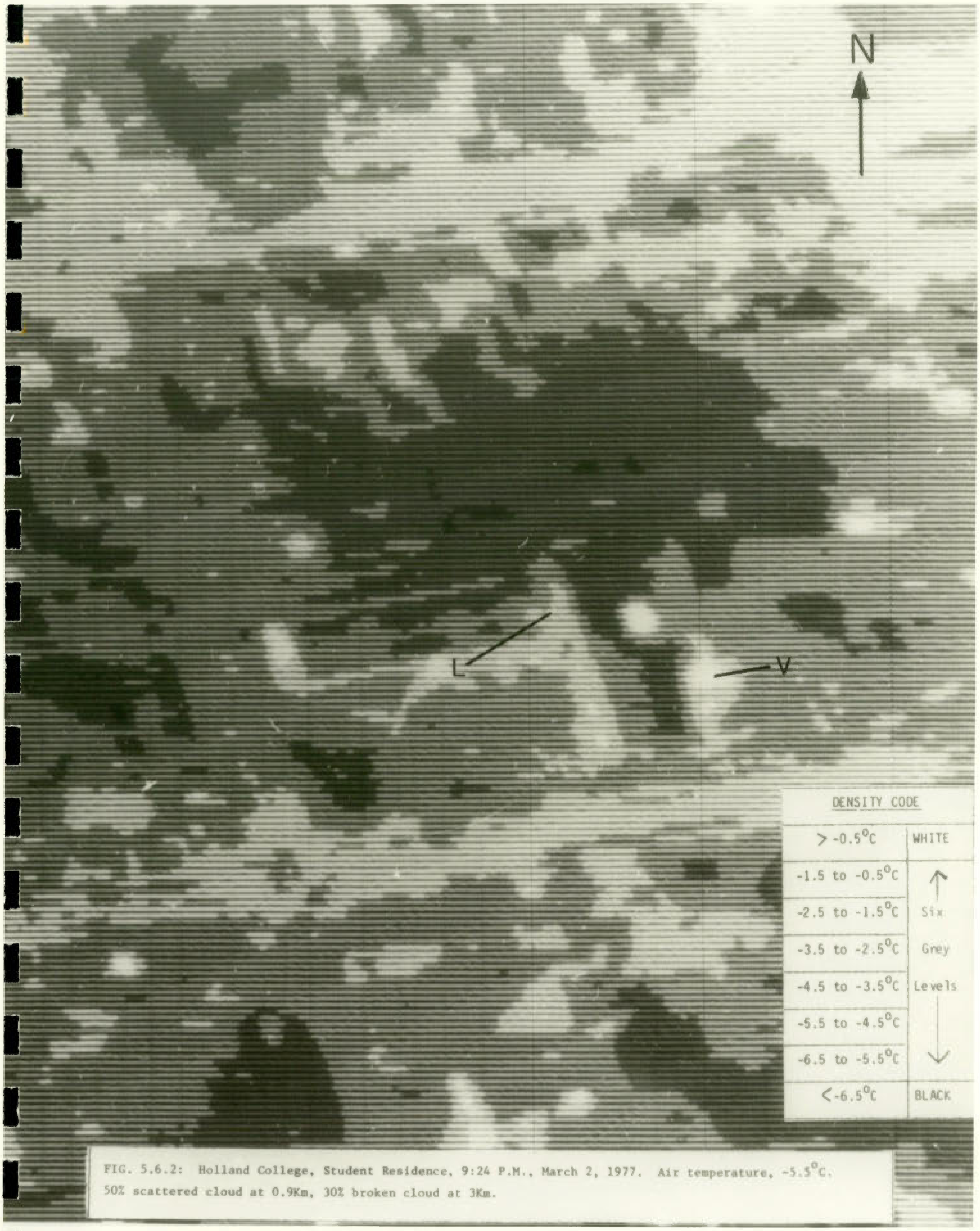


FIG. 5.6.1: Holland College, Student Residence, 11:24 P.M., March 26, 1978. Air temperature, -8.6°C. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.



DENSITY CODE	
> $-0.5^{\circ}C$	WHITE
-1.5 to $-0.5^{\circ}C$	↑
-2.5 to $-1.5^{\circ}C$	Six
-3.5 to $-2.5^{\circ}C$	Grey
-4.5 to $-3.5^{\circ}C$	Levels
-5.5 to $-4.5^{\circ}C$	
-6.5 to $-5.5^{\circ}C$	↓
< $-6.5^{\circ}C$	BLACK

FIG. 5.6.2: Holland College, Student Residence, 9:24 P.M., March 2, 1977. Air temperature, $-5.5^{\circ}C$. 50% scattered cloud at 0.9Km, 30% broken cloud at 3Km.

5.7 Robertson Library, U.P.E.I.

1978 and 1977 thermographs are in Figure 5.7.1 and 5.7.2.

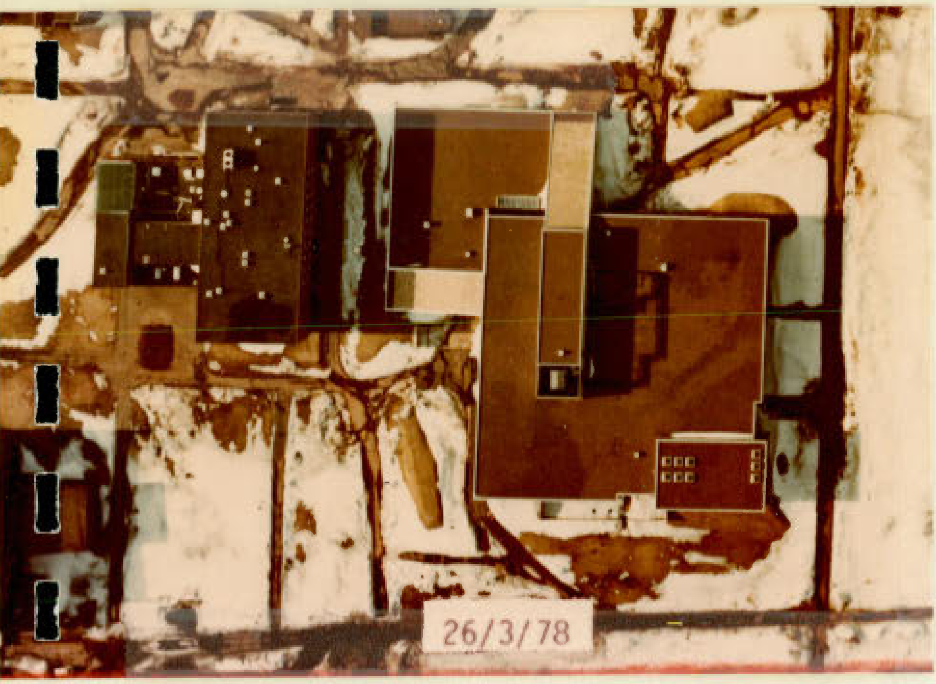
This building houses the computer centre and the main library L at U.P.E.I. The roof of building C is 3 metres lower than building L. The sections 1 and 2 slant from the higher to lower elevation.

This inverted roof building has an apparent cooler temperature in 1978 than in the 1977 thermograph. A possible cause is lowering of thermostats on a holiday weekend in 1978.

The 1978 thermogram has three of the bright spots which can be seen in the 1977 data. Points 3 and 4 are ventilators; point 5 is a large glass skylight. The bright spot 6 appearing only in the 1977 thermogram is due to a large roof access door being open. This was the control roof in 1977 and project personnel were on it when the thermograph data was being collected. Access to the roof was gained through this large door which was left open.

The point marked 7 on the 1978 thermogram is a vent. It was obviously not operating when the 1977 thermogram was taken.

The most interesting parts of the roof are slanting section 1 and 2. Section 1 appears to be warmer than the other parts in both 1977 and 1978. These slanting sections are composed of 4 cm. of foam insulation held down by 60 x 60 x 5 cm. concrete paving stones (see P1). Roof 1 faces west and is warmed longer by the afternoon sun than roof 2. It is also influenced by its proximity to the walls (with windows) of the Duffy Sciences Building D. Roof 2 faces north and is not close to any vertical walls. One would expect the temperature of the concrete slabs to cool more slowly after sunset than the loose gravel on the flat portions of the roof because of cold air circulation through the gravel layer.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P-1 MAY 8, 19

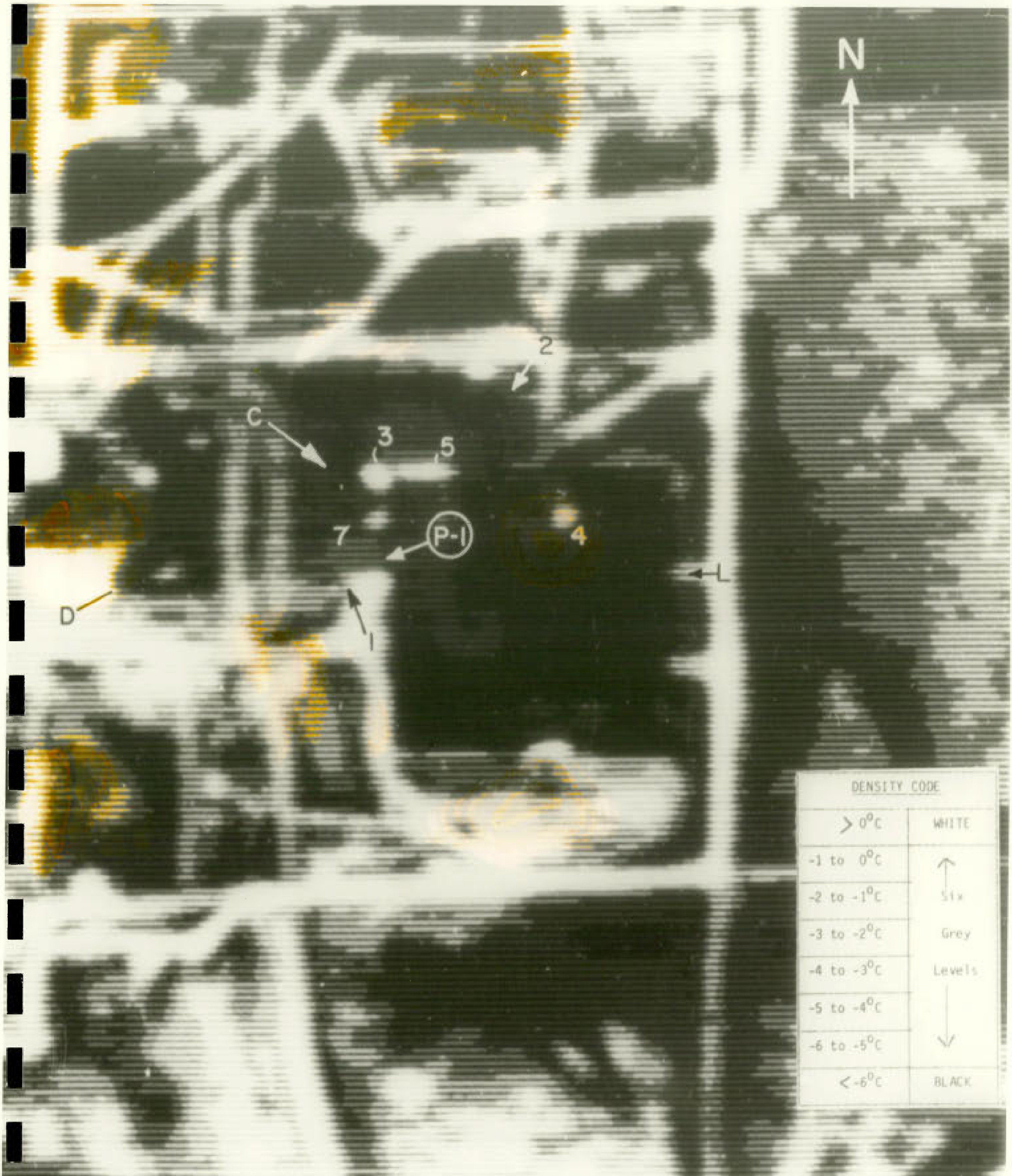

FIG. 5.7.1: Robertson Library, University of P.E.I., 11:18 P.M., March 26, 1978.
Air temperature, -8.6°C. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.

FIG. 5.7.2: Robertson Library, University of P.E.I., 9:18 P.M., March 2, 1977. Air temperature, -5.5°C. 50% scattered cloud at 0.9Km, 30% broken cloud at 3Km.

5.8 Dairy Processing Plant

Thermograms for 1978 and 1977 are in Figure 5.8.1 and 5.8.2.

This plant contains two cold storage areas 1,2. In the 1977 thermogram, area 1 was very evident as having a warmer temperature than some of the surrounding roof surfaces and was clearly outlined. This additional brightness was interpreted as being caused by a combination of solar heat being retained in a thick sheet of ice and relatively high emissivity of an ice surface. In 1978 these surfaces are not as well delineated in the thermogram although they are readily discernible in the air photo. The change in thermal expression from 1977 to 1978 occurs because much of the thick snow and ice cover has disappeared with the advance of warmer weather. With the disappearance of the snow and ice cover, the thermal variation takes on a more broken characteristic pattern, especially at the larger of the two areas.

An L-shaped addition has been made to the original L-shaped penthouse. Although the surface of the old and new sections are clearly different in the visible spectrum as seen from the air photo, their thermal signatures are very close, the north part of the new surface being (slightly) the coolest of the combination.

Area 3 is the roof of a drying plant for powdered milk. In 1978 this room was not in use and was allowed to remain cooler than the remainder of the building. The geometric shape of the inside room is revealed very clearly in the thermogram. The effect on the radiative temperature of the roof over this room has been to reduce it to the next lower grey level. In 1977 the room was in use and its roof was at essentially the same radiant temperature as the rest of that section of the building.

Building H is the boiler room.

The cool objects at 4 are trucks parked on the ground.

Warm spot 5 is the boiler room and chimney stack of a sports arena east of the dairy plant.

The most interesting and useful part of the analysis for this site was the research at the site needed to account for the warm tone on the west side of the roof on building 9 (P-1) and the two warm spots, 6,7 on the north edge of the roof on building 8. In the three cases damaged insulation has found on the interior of the building which would readily account for the temperature rise. The ground floor of these two buildings house different operations related to the labelling and packaging of canned milk. The second floor however is a large common storage area with no ceiling. A large stock of paper containers, principally cardboard boxes is kept here. The space is clean, evenly heated and not too humid. Air movement is good because there is a 45 cm. wide walk-way between the outside wall and the piles of stock. The walkway is provided for cleanliness inspection. Insulation batts with an attached vapour barrier are installed between the roof rafters. The whole assembly is covered with standard sheets of white fibre board. The insulation thickness is 7 cms. in building 8 and 7 cms. in building 9.

Detailed examination of the overhead region of the walk-way along the north side of building 8 revealed missing insulation at 6. Approximately 1 x 4 metres of insulation had been ripped away to permit installation of a can-carrying chain belt. See P-2. No attempt had been made to repair the damage or close off the broken vapour seal. The roof sheathing lumber was exposed where the insulation had been removed. This chain conveyor runs along the north and west sides of building 9 at the second-floor level. Inspection of the roof over this conveyor run revealed large sections of missing insulation on building 9, see P-3, P-4. This insulation had been removed at intervals to suspend the conveyor from the roof. To keep the paper stock clear of dirt from the chain conveyor, a floor-to-roof partition, running almost the entire north-south dimension of building 9 was installed. It is about 2 metres from the west wall of the building. The space defined by the partition and the west wall is long and narrow, with a row of windows in the outside west wall. A strip of the floor has also been removed to allow mechanical access to the conveyor from the ground floor. The accumulated effect of missing insulation, heating from the windows, and convection from the ground floor causes the warmer thermal signature over this section of the building.

The warm spot at 7 coincides with a roof drain shown in P-5. It is suspected that when the roof drain was installed the insulation was removed and not replaced as is the case with other alterations in this building. This could not be verified directly because the area was not physically accessible.

The significant features found in this set of thermograms are:

a) the detectability of a change in interior temperature of the building at location 3, and

b) the reproducibility of the heat-loss effect from year to year as revealed at locations 6 and 7 and the western side of roof 9.


26/3/78


P-1 MAY 8, 1978.
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8


P-2 MAY 9,


P-3 MAY 9, 1978.


P-4 MAY 9, 1978.


P-5 MAY 9, 1978.

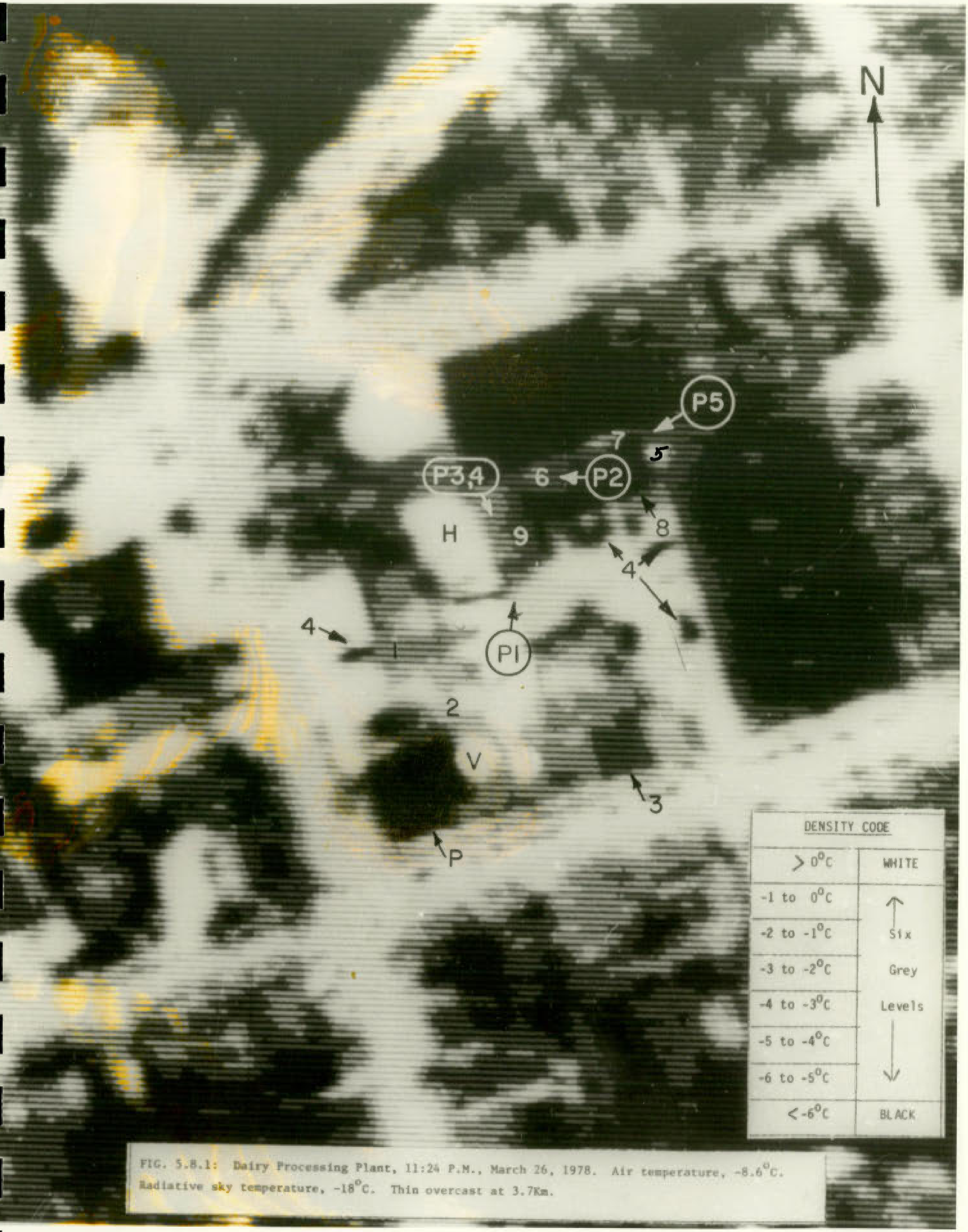


FIG. 5.8.1: Dairy Processing Plant, 11:24 P.M., March 26, 1978. Air temperature, -8.6°C. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.

FIG. 5.8.2: Dairy Processing Plant, 9:24 P.M., March 2, 1977. Air temperature, $-5.5^{\circ}C$. 50% scattered cloud at 0.9Km, 30% broken cloud at 3Km.

5.9 Commercial Store - Mall

Thermograms for 1978 and 1977 are in Figures 5.9.1 and 5.9.2.

There are significant changes from 1977 to 1978 in the thermograms for this building. For ease of description the roof has been divided into four sections. Sections 1, 2, and 3 have a common open sales area. The elongated strip S, along the west side of the store, is a storage area.

Permission to visit the roof was not readily available, nor was accurate information as to the roof's design. Two opinions were given on the roof design, one in 1977 and one in 1978 but the opinions are at variance with each other in the matter of where the insulation on the roof is.

Ground truth was obtained in 1978 from a store employee who claimed to be familiar with the building. According to this source, the roof of the building leaks in a large number of places, the water penetration being so severe as to require children's swimming pools to be placed on the ceiling girders to hold the water. Water penetration into the storage room is such that stock is kept on platforms and covered with polyethylene sheets to keep it dry. According to this employee, the outer roof is constructed or a layer of black construction-type sheathing overlaid with felt paper, tar and gravel. Glass wool insulation, with a self-contained vapour barrier is installed on the inside of the roof.

When the building was visited in 1977 no one could give details of the roof construction except that it was "semi-rigid". One informant believed it might have been a type of glass wool insulation that has a hard surface (usually intended for painting) bonded to one side. According to this source the insulation had been laid on the outside side of the roof deck with the hard side up and then covered with a standard tar and gravel membrane. Such a surface would soften with time from water saturation to produce the effect of being soft under foot. (Other building superintendents visited in Charlottetown describe "semi-rigid" insulation as the black sheathing commonly found in frame house construction. This material is made from natural fibres and would also soften after extended saturation with water, especially during hot summers).

When the roof was visited in 1977 part of the surface on section 1 was spongy to walk on. The large rib-like, cooler features in the central part of section 1 on the 1977 thermogram were dry and slightly raised and appeared to be more robust under foot than the surrounding area.

A portion of the roof was repaired in February 1978. From the description given by a clerk in the store, the repaired section would coincide with section 1. No reliable details of the repairs could be obtained. The air photo for 1978 shows flashing missing along the east side of section 1 and part of section 2.

If an interpretation of the warm signature over section 1 of the roof were carried out without any knowledge of the water leakage to the interior of the building, location W and S would likely be interpreted as partially-frozen water-ice mixtures because the temperature is approximately $0^{o}C$ and there is a fairly good correlation between these regions and the dark patterns (presumed to be water) on the aerial photo. There is also some correlation between what appears in the air photo to be ice at the edge of a puddle with the edge of a warm area. See point E for example. Because of the extent of the incompletely-frozen water (as inferred from the thermogram) however, some unusual features such as unusually deep depressions in the surface would be expected in order to account for such large areas being in this condition so late at night. Or, in light of what is known about the building, the possibility of anomalous heat loss contributing to the slow freezing of the water must also be considered a definite possibility.

The same reasoning would apply to region S, the roof over the storeroom except that S, having a fairly rectangular pattern, would be even more suspect as a region of excess heat loss because of the regular pattern of the warm area.

Some of the regions of the roof adjacent to W and S are colder than $-6^{o}C$; the temperature on W and S is in the -1 to $0^{o}C$ band or greater than $0^{o}C$. An exact assignment cannot be made due to too small a change in contrast on the thermogram near the white levels. Anomolous heat loss by itself is not likely to be the cause of these large temperature changes because other confirmed instances of heat loss cause a temperature shift in the order of a degree. The interpretation therefore must be in doubt until additional information about heat loss and/or the contour of the roof over section 1 can be obtained. In the meantime the large warm areas at W and S are interpreted as large areas of standing water that are slow to freeze completely because the water is either unusually deep or is being kept from freezing by anomolous heat transmission through the roof under it.

The main body of section 2, section 3 and section 4 exhibit a satisfactory thermal signature as does a limited region on section 1.

Region 6 in the 1977 data is an excellent example of a water/ice mixture. The radiant temperature on the 1977 thermogram is approximately $0^{\circ}C$ and the warm feature corresponds with a puddle in the air photo for 1977. In 1978 there is also a puddle in the air photo but it is presumed to have been shallower and therefore completely frozen and at equilibrium with the surrounding dry roof by the time the thermography was taken so that only small regions of it exhibit a change in contrast and those are within the limits expected from a change in emissivity without a change in temperature.

The thin slightly warm strip at 5 is the store sign over the entrance. The snow drift behind the sign was ruled out as the source of this warm feature, because it is continuous, whereas some of the scan lines don't contain the lighter tone.


26/3/78

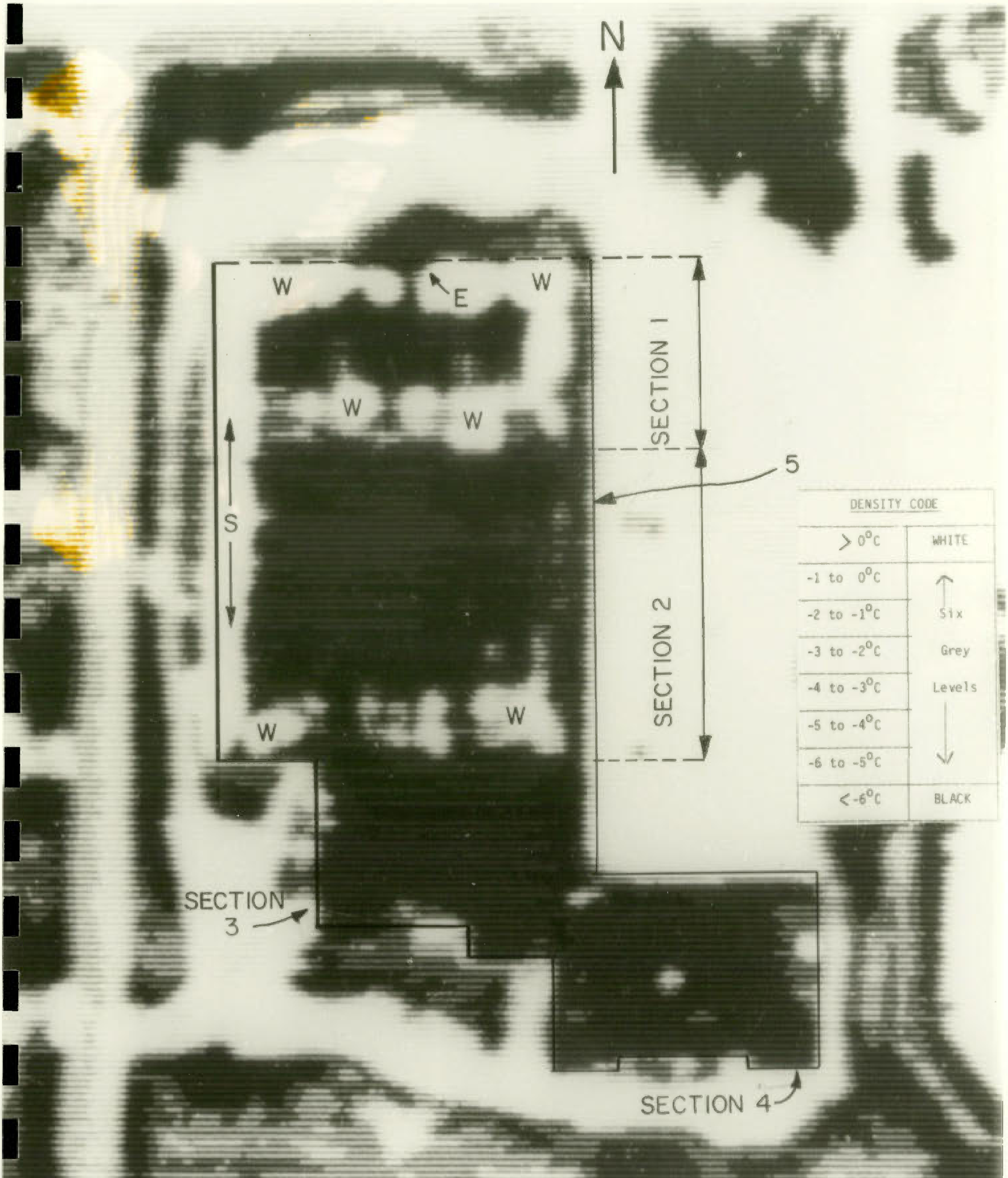


FIG. 5.9.1: Commercial Store - Mall, 11:10 P.M., March 26, 1978. Air temperature, -8.6°C. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.

DENSITY CODE

> -0.5°C	WHITE
-1.5 to -0.5°C	↑
-2.5 to -1.5°C	Six
-3.5 to -2.5°C	Grey
-4.5 to -3.5°C	Levels
-5.5 to -4.5°C	
-6.5 to -5.5°C	↓
< -6.5°C	BLACK

FIG. 5.9.2: Commercial Store - Mall, 9:13 P.M., March 2, 1977. Air temperature, -5.5°C. 50% scattered cloud at 0.9Km, 30% broken cloud at 3Km.

5.10 Heavy Machinery Depot

Thermograms for 1978 and 1977 are in Figure 5.10.1 and 5.10.2.

This roof has sections at several elevations, the locations of which must be understood to understand the thermograms. The roofs of the western wing W, and the penthouse P are about 3 metres higher than the rest of the building. The elevation of the sections over the eastern half of the building is also broken up by smaller height changes. The southern half of the eastern section containing the eight skylights is the highest. This southern half is an inverted-design roof. The northern section (darkest in the air photo) is also at two heights; there is a slightly raised section 1 beside section W, see P-1 and P-2.

Snow is lying on the western end of 1 in the shadow of W and feeding a dark puddle of water (this water can be seen on the air photo and was confirmed the morning after the thermography was taken). The surface under this puddle is very flat, and has no drains, water runs off the edge (see arrow P-1) and drops about 1/2 metre to a very concave section, containing drains. This section is readily identified by the long black strip 2 of oily soot lying along its lowest part (see 2 on P-2). The section with the skylight has several drains nestled in the heavy crushed rock that is characteristic of inverted roofs. The most striking feature of the 1978 thermograph is the complete absence of any contrast change in the infrared expression of the standing water on section 1 containing the melted snow. It is concluded that the water had time to freeze completely and came to equilibrium with the ambient air temperature. By contrast, the 1977 thermograph has a warm strip originating at or near this section and continuing around the drains. It is concluded that in 1977 the infrared data was taken too early in the evening for the water to freeze and stabilize to the local air temperature.

It is also probable that in 1977 the building, having been in use all day, was warmer inside. There is some other indication of this in comparing the thermographs for 1977 and 1978 for their overall appearance. In 1978 the roofs of the whole building had stabilized to a very uniform temperature. In 1977 the effect of convection heating of the roof at spot 3 over the inside welding deck was readily observable causing a non-uniform temperature profile due to local internal heating.

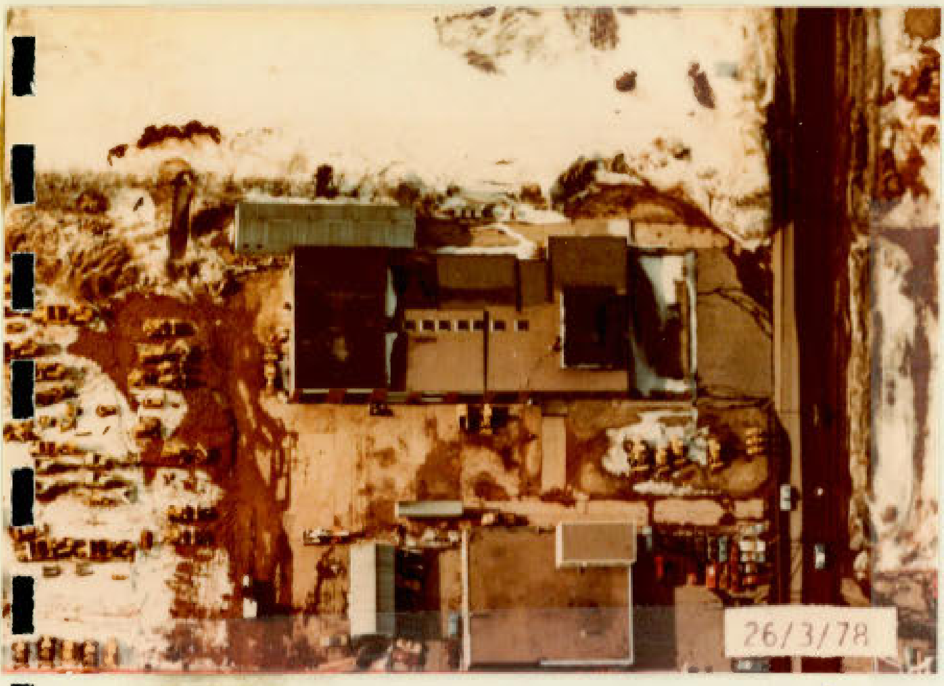
Warm area 4 is in the vicinity of the stack.

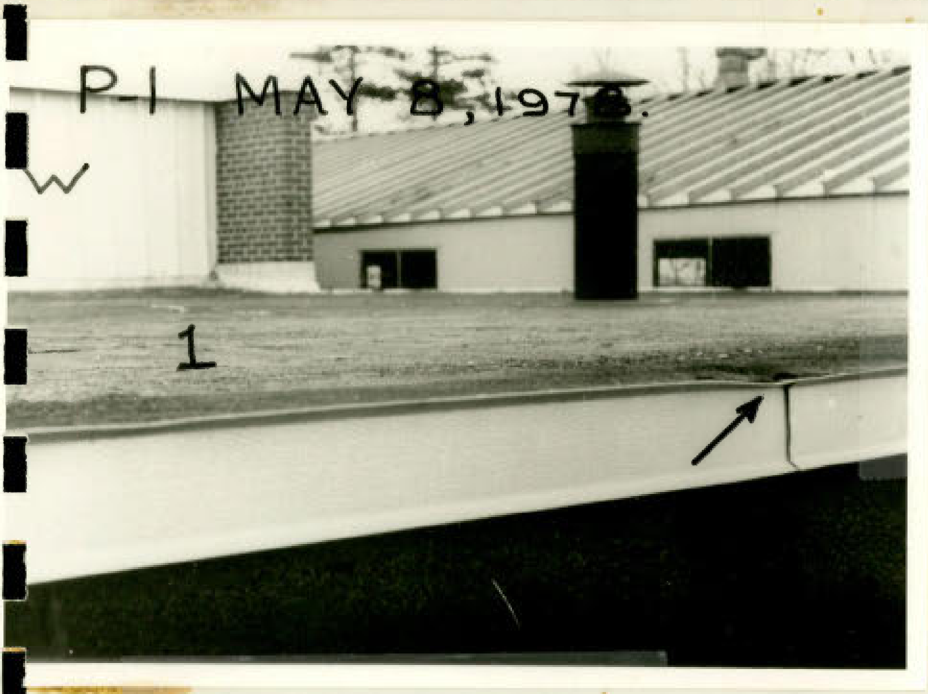
Strip 5, at an intermediate temperature, is believed to be caused by heating from the windows of the penthouse.

Area 6 is not part of the building. It is a raised lawn on which equipment is placed for display. It is noticeably warmer in 1978 than in 1977 because the lawn is clear of snow and is absorbing solar heat very effectively.

The skylights 7, are about 2 metres on a side and conveniently fill one scan line. There are eight skylights, four can be seen in P-3.

The most interesting feature at this site is the confirmed presence of water on the roof in 1978 and the fact that when frozen and allowed to come to thermal equilibrium with the surrounding dry surface, the total, (ie. emitted and reflected) infrared signal received from the ice surface blends completely with the total infrared signal received from the surrounding dry surface under the sky-temperature conditions prevailing when the infrared data was taken.


26/3/78


P-1 MAY 8, 1978.
W
1


P-2 MAY 8, 1978
2
1


P-3 MAY 8, 1978.

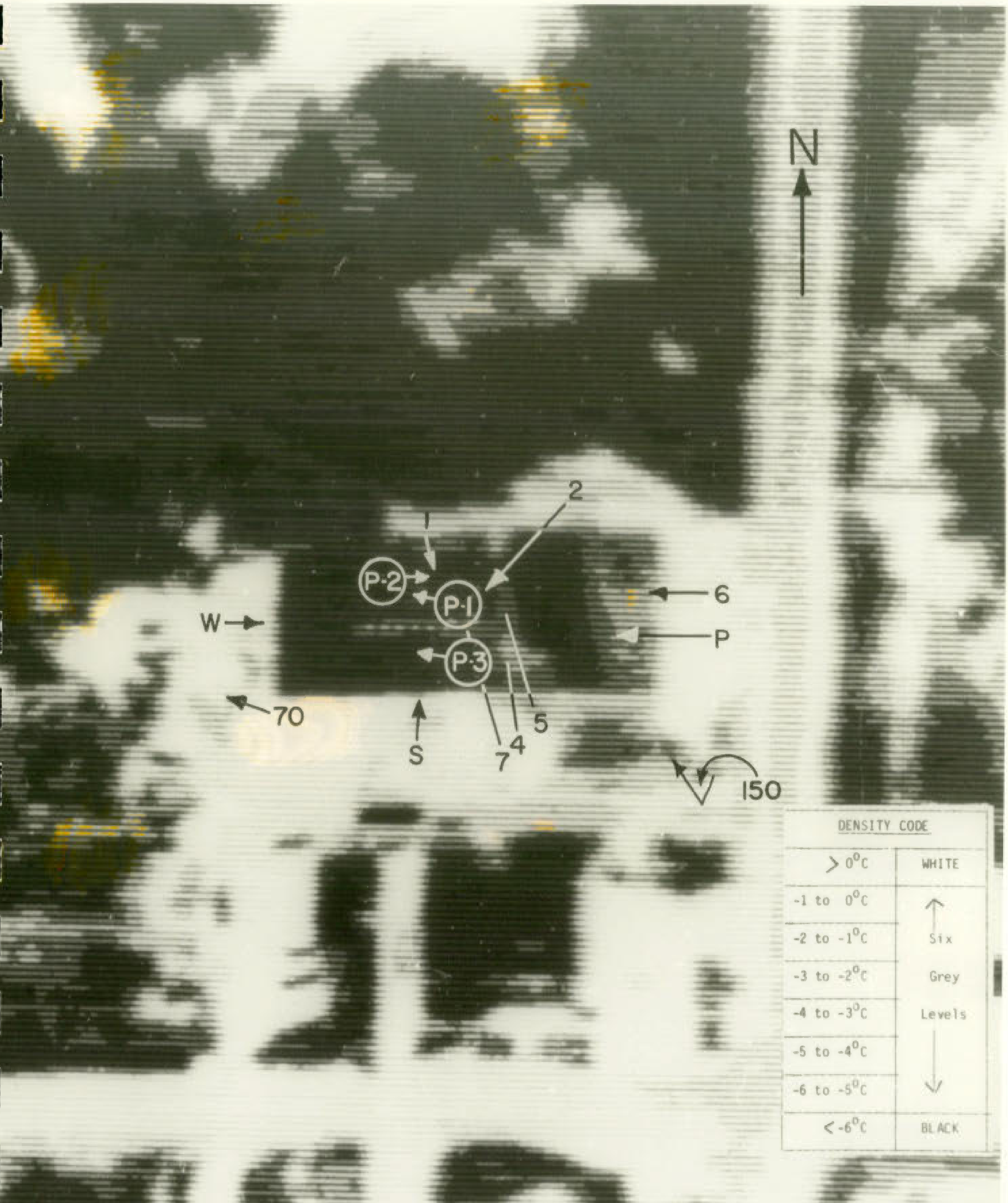


FIG. 5.10.1: Heavy Machinery Depot, 11:10 P.M., March 26, 1978. Air temperature, -8.6°C. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.

FIG. 5.10.2: Heavy Machinery Depot, 9:13 P.M., March 2, 1977. Air temperature, $-5.5^{\circ}C$. 50% scattered cloud at 0.9Km, 30% broken cloud at 3Km.

5.11 Birchwood Junior High School

Thermograms for 1978 and 1977 are in Figures 5.11.1 and 5.11.2.

The roof of the school is at three elevations. Roof 3 is the lowest and access was gained through the window W of a classroom in building 1, see P-1. Building 2 is the gymnasium, it is about 1 metre higher than building 3 and 2 metres lower than building 1.

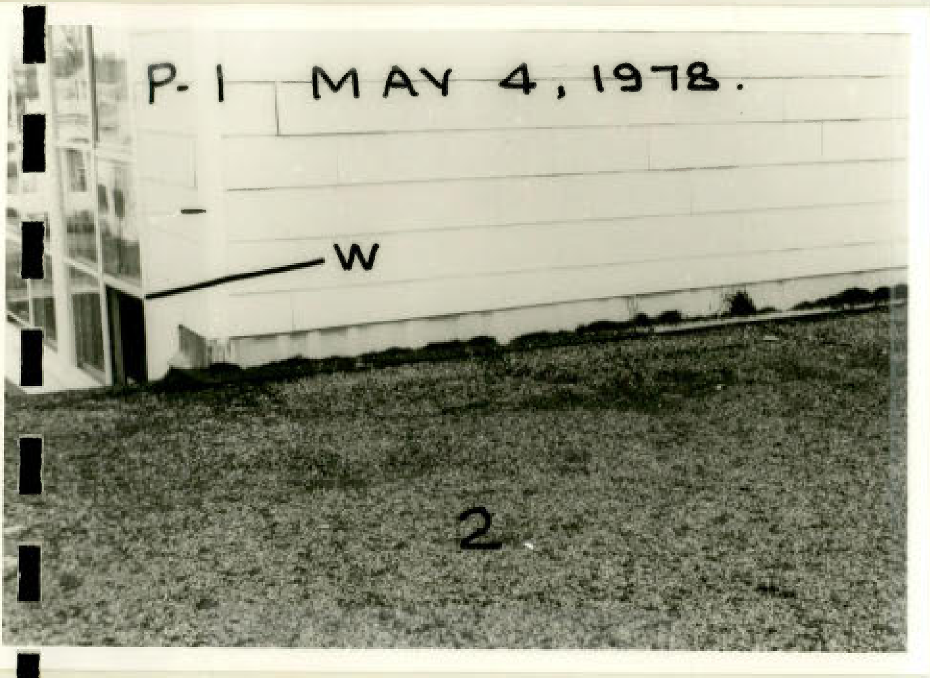
As a general observation, roof 1 was warmer than the other two in 1977 whereas in 1978 all three roofs are at the same temperature. The superintendent commented on this fact by noting that the thermostats are continually being adjusted but he could give no definite reason. No doubt the interior temperatures stabilized in 1978 after being empty for several days.

In the 1977 thermogram, there is a long snow drift at S. This drift had a warm tone due to its being close to radiation from a row of windows along the upper wall of the gymnasium. In 1978 there is a snow drift, but it is noticeably smaller and not as high and there is no discernible effect from the windows. In the light of what has been learned about water-ice mixtures in the present study, the warm strip in 1977 is probably due to a combination of a warm snow surface close to the building and standing water and ice on the roof. In the thermograms for both years there is a large snow drift very similar in size at D. These drifts correlate with regions of intermediate temperature. They are directly outside the windows W (P-1) and are heated on the surface by the radiant heat from the windows which are of single-glazed design. The bright spot at 4 in the 1978 thermograph is interpreted as being due to water and ice.

There is a small patch of snow 5 near the north-east corner of the gymnasium and close to the wall rising to the roof of building 1, see P-2. This snow is feeding a shallow puddle of water 6. On the thermogram this spot has a warmer thermal expression which is interpreted as water/ice or ice that has not yet cooled to the ambient temperature. The building superintendent noted that water frequently collects at this point because it is slightly lower than the drain. A search for water leaks was made on the interior of the building but none could be found and none have ever been reported. It was concluded that the probability of anomalous heat loss is low.

Comparison of the Birchwood Junior High School thermographs for 1977 and 1978 illustrate how <u>the thermal expression of a roof can change with a change in conditions inside the building</u>. The thermal patterns in the 1977 thermogram are characteristic of a building whose interior temperatures are being significantly affected by transients in the thermal load because of activity in the building. The 1978 thermograms are characteristic of the more uniform interior temperatures expected from closing the building and allowing the interior temperatures to stabilize.


26/3/78


P-1 MAY 4, 1978.
W
2


P-2 MAY 4, 1978.
1
2

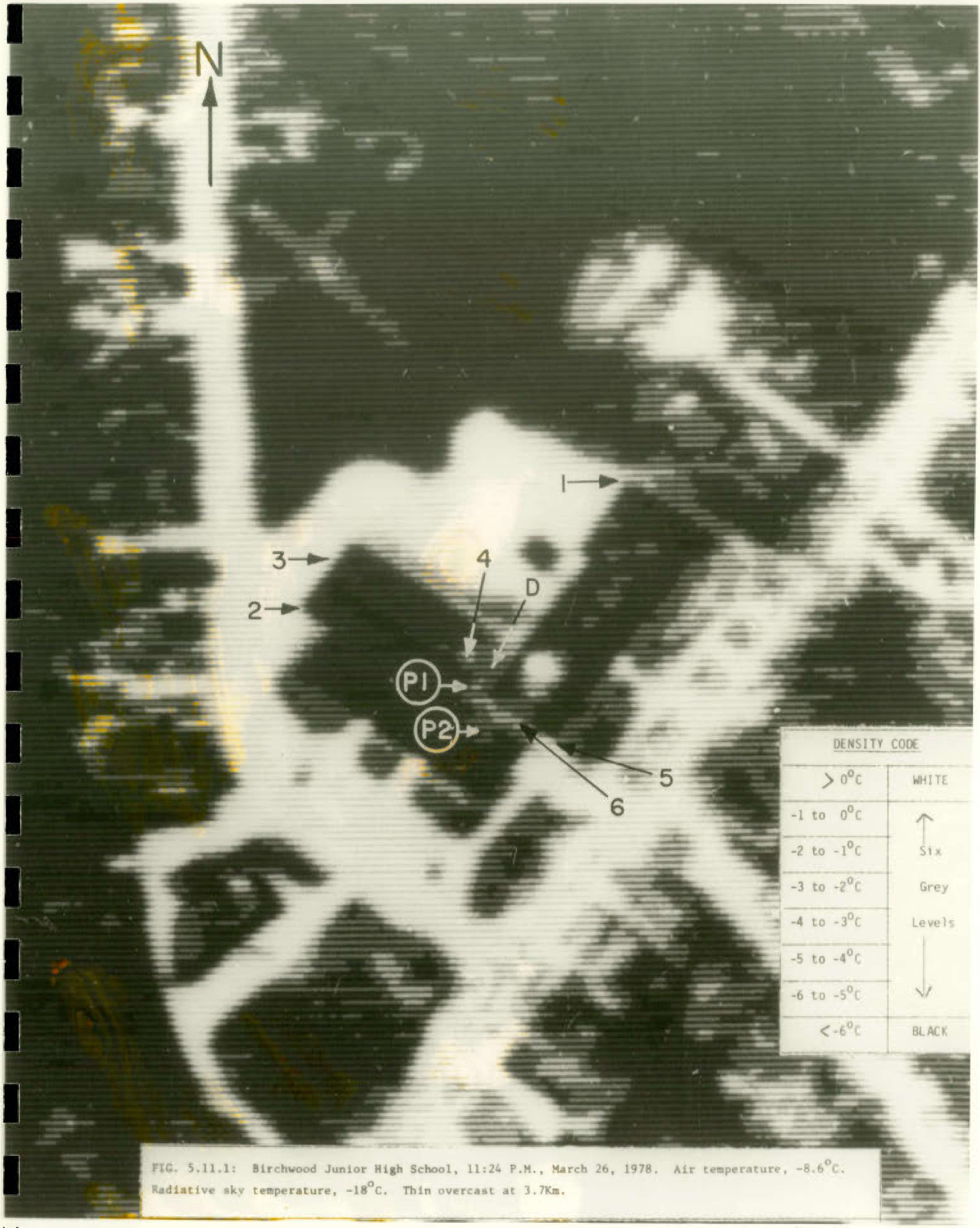


FIG. 5.11.1: Birchwood Junior High School, 11:24 P.M., March 26, 1978. Air temperature, -8.6°C. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.

FIG. 5.11.2: Birchwood Junior High School, 9:24 P.M., March 2, 1977. Air temperature, $-5.5^{\circ}C$. 50% scattered cloud at 0.9Km, 30% broken cloud at 3Km.

5.12 Confederation Centre

Thermograms for 1978 and 1977 are at Figure 5.12.1 and 5.12.2. respectively.

The general thermal expressions of five of the six buildings is unchanged from 1977 to 1978. The extension of the hot zone around the stack at 7 to area 8 in 1977 is absent in 1978. What was suspected as being wet and losing heat in 1977 is now interpreted as being wet and not at equilibrium with the surrounding dry parts of the roof.

The most striking change in the thermogram is roof 6 of the underground garage. In 1977 this roof was quite warm, in 1978 it is at the same temperature as the rest of the building. When the site was visited some five weeks after the 1978 thermography was taken, no accurate information could be obtained as to the actual state of the roof of the underground garage on the day in question but it was in the process of being completely re-insulated.

Both the 1977 and the 1978 thermographs show a tendency for roof 2 to be warmer along the west side with a distinct temperature profile which is consistent for the two years. No explanation could be found for this save what was suggested in 1977, ie. the method of installing the insulation may have led to uneven performance. The same effect, though less pronounced, can be seen on the buildings 4,5, and 6. Roofs 2,4,5, and 6 are scheduled for refurbishment in 1978 and evidence of preparatory work can be seen on building 2 in the air photo.

Repairs to roof 3 were completed before March 26, 1978. None of the roofs are believed to have failed, the refurbishing is being done as part of a centre-wide undertaking to add extra insulation to the inside walls and the roof.

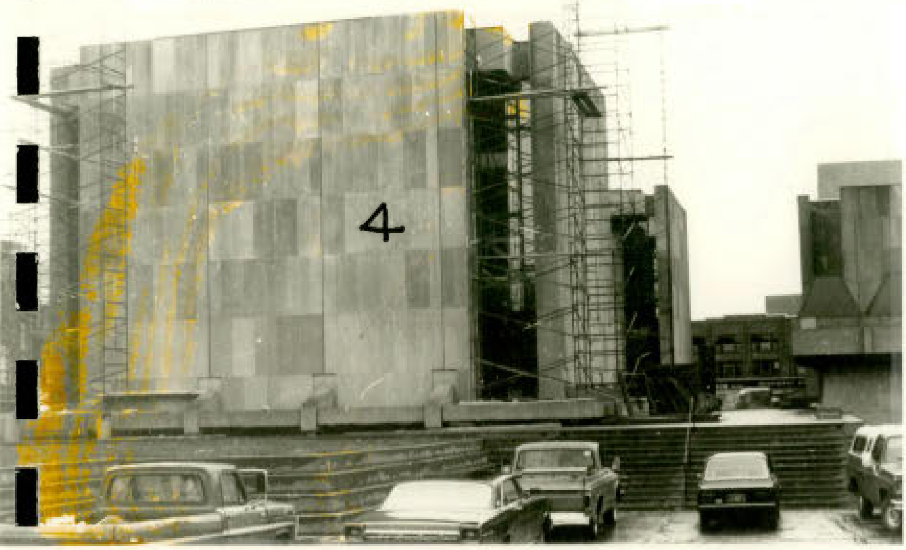
The vertical walls of the building are windowless (see P-2). This feature would ordinarily reduce the edge effect considerably but they are poorly insulated (see P-1) with 3 cm. of foam slab, some of which has been installed with a wide gap between the sheets. The broken pieces in P-1 was probably caused by the removal of the facing stone.

In summary, comparison of the thermographs of roofs 2 and 6 for the two consecutive years shows both consistency in the thermal performance of a roof from year to year and consistency in the remotely sensed thermal infrared data. In the case of a change in the state of a roof on the other hand, as is the case of the roof of the underground garage, comparison of the year-to-year thermography reveals the change clearly.


26/3/78


P-1 MAY 9, 1978

P-2 MAY 9, 1978.



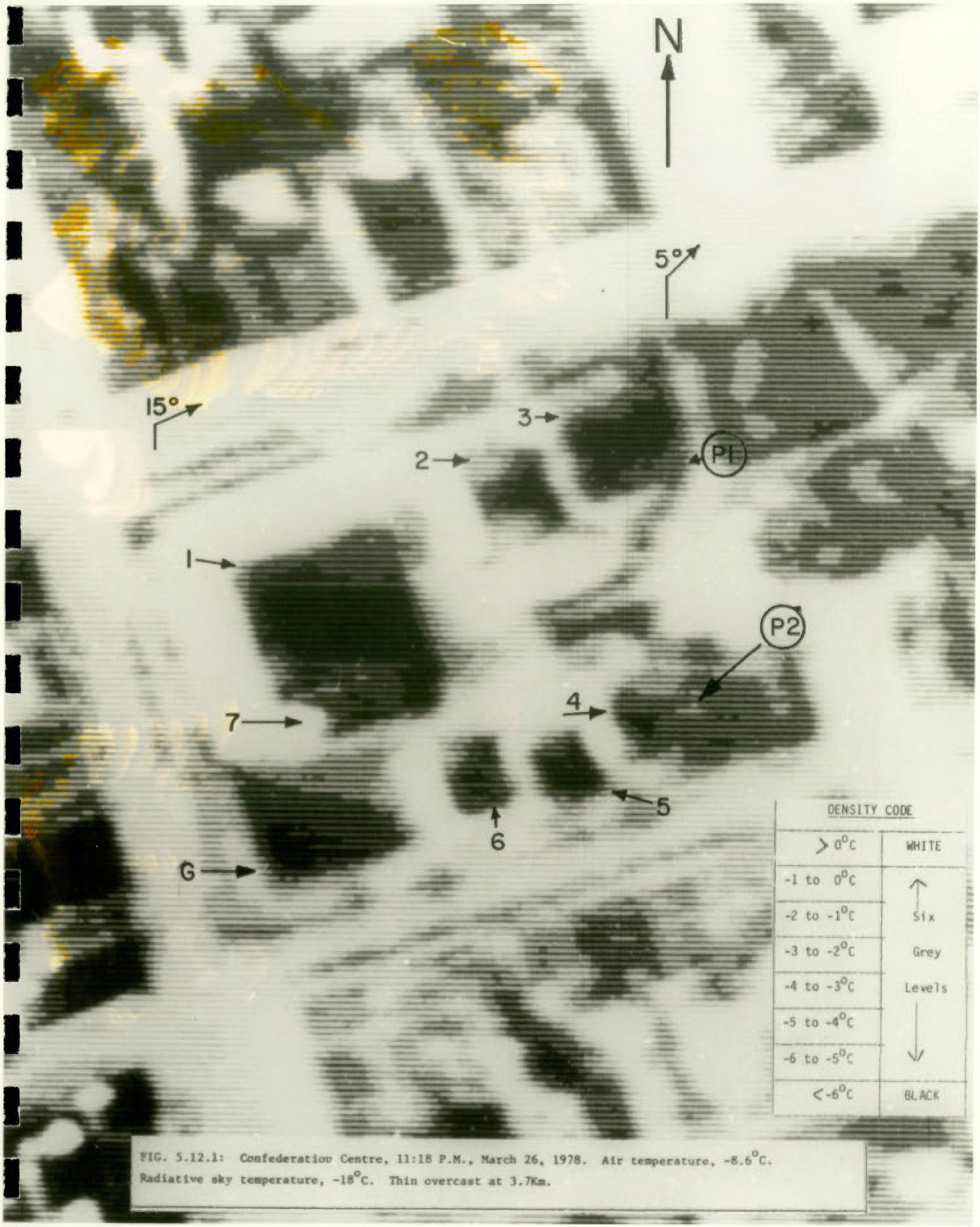


FIG. 5.12.1: Confederation Centre, 11:18 P.M., March 26, 1978. Air temperature, -8.6°C. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.

DENSITY CODE	
> -0.5°C	WHITE
-1.5 to -0.5°C	↑
-2.5 to -1.5°C	Six
-3.5 to -2.5°C	Grey
-4.5 to -3.5°C	Levels
-5.5 to -4.5°C	
-6.5 to -5.5°C	↓
< -6.5°C	BLACK

FIG. 5.12.2: Confederation Centre, 9:13 P.M., March 2, 1977. Air temperature, -5.5°C. 50% scattered cloud at 0.9Km, 30% broken cloud at 3Km.

5.13 Charlottetown Hospital

Thermograms for 1978 and 1977 are in Figure 5.13.1 and 5.13.2.

The uninsulated roof U is quite evident in the data for both years.

It was learned that several roofs had been replaced. Roofs 1 and 3 are of conventional design and were re-built to the same specification about 5 years ago by the same contractor. The warm roof 1 in the 1978 print was discernible in the 1977 data although less prominently. No explanation was given for 1 being warmer than 3. The interior use of both buildings is similar and both buildings are occupied and heated to the same approximate temperature on the top floor. The possibility of thinner insulation at 1 was ruled out by the building supervisor. The only difference that could be definitely established is that the building at 1 is very old (the original hospital) whereas 3, the nurses' residence, is comparatively new. P-1 is a photo or roof 1. It is quite possible that the old building has a poor (or non-existent) air circulation system and the upper stories tend to be warmer than the upper stories of the nurses's residence due to uncontrolled convection of the warmer air, but no confirmation of this thesis could be obtained at the site. Roof 2 is of inverted design and was re-built by another contractor.

Examination of roof N, which is T-shaped and covers the newer wing of the hospital, shows a trend to being warmer at the east end in 1977 and warmer at the west end in 1978. The difference may be small, bearing in mind that a single change in density in a level-sliced thermogram can be caused by a small fraction of a degree, but the bias seems to be present nevertheless. When this effect was discussed with the superintendent it was learned that roof N and roof 2 are separated from the warm ceiling of the top occupied floor of the building by a crawl space which is ventilated to the outside. See V on P-2, P-3, P-4. The crawl space volume is broken up by steel beams which would impede but not block the flow of air. The crawl space is windy and dusty if it is windy outside. The temperature of the roofs would therefore be expected to be influenced by the prevailing winds while still being fairly well coupled radiatively to the ceiling. It is tentatively suggested that the reversal in the temperature bias of roof N from 1977 to 1978 is due to different wind directions both years. In 1977 the wind was from the west and southwest all day and varied from 10 to 20 km/hr during the day. In 1978 the wind was from the west early in the day, changed to the north in the early afternoon, northeast in the early evening and east towards midnight. The general trend during the day was to an increase in velocity from 11 to 19 km with the peak at mid-day while it was changing from northwest to north northeast.

The warm area at 4 on the thermographs for both years is noticeably smaller in 1978. After a careful study of the geometry of the door of the penthouse and a hot air exhaust duct located about 1 metre west of the penthouse door and two meters above the level of the roof (P-5) it is concluded that feature 4 is due to surface heating of the roof by the hot air exhaust in both years. The extension of this warm area to the east in 1977 coincides and is due to partially frozen standing water which had cleared by the time the air photo for 1977 was taken 1 1/2 days later. It was confirmed that water tends to collect at this point on the roof because of its slope.

Warm spot 4 blends into some edge effect 5 on the east side of the penthouse in 1977.

In 1977 warm air was being exhausted at point 6, but no details were available as to why the same feature is barely visible in 1978.

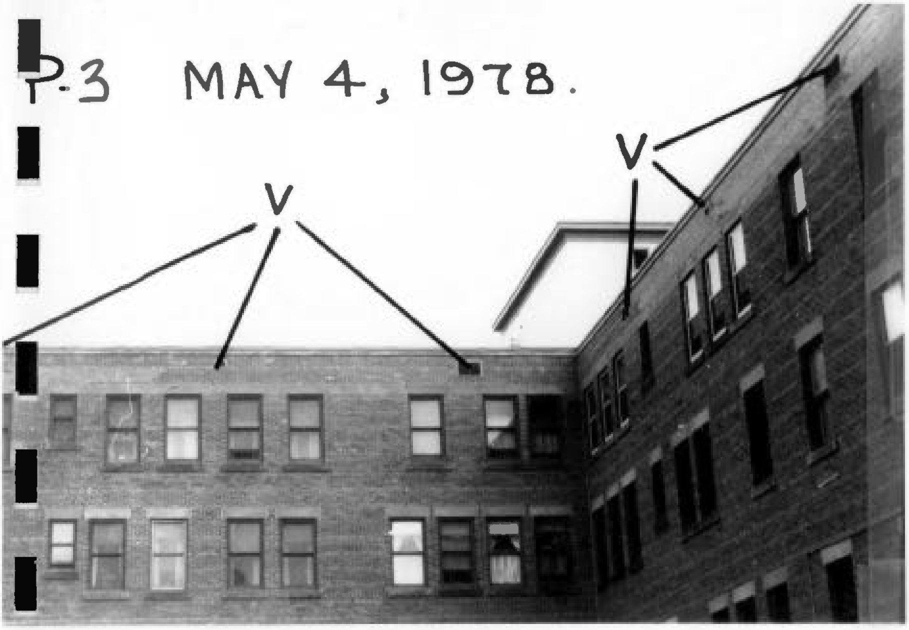
In general, the thermal expression of the roofs of the hospital and the nurses' residence are uniform and consistent between 1977 and 1978 with the exception that roof 1 is more clearly delineated in the 1978 data.

The comparison of the thermograms for this site for both years illustrates how a change in the overall contrast on a roof - in this case the reversal of the temperature trend on roof N - can frequently be attributed to a change in the environment below the roof.


26/3/78


P-1 MAY 4, 1978.
I


P-2 MAY 4, 1978.
V


P-3 MAY 4, 1978.
V
V


P-4 MAY 4, 1978.
V


P-5 MAY 4,

FIG. 5.13.1: Charlottetown Hospital, 11:10 P.M., March 26, 1978. Air temperature, -8.6°C. Radiative sky temperature, -18°C. Thin overcast at 3.7Km.

FIG. 5.13.2: Charlottetown Hospital, 9:13 P.M., March 2, 1977. Air temperature, -5.5°C. 50% scattered cloud at 0.9Km, 30% broken cloud at 3Km.

6. Conclusions

6.1 The Control Roof

The following conclusions have been drawn from the experimental data and the theoretical analysis of the control roof:

(i) The temperature distribution over roofs that are partially covered with water or ice can be established from an aerial thermogram through the use of the simple partial spraying procedure. This procedure will yield a quantitative value for the change in the brightness temperature in going from a dry to a wet (or frozen) region of a roof. The value so derived will take into account the differences in emissivities of the two surfaces and the net effect of sky radiation reflected off them.

(ii) The availability of the correct temperature distribution on a thermogram allows an interpreter to immediately screen out as "safe" regions on a roof that can be related to wet spots in an aerial photo if the increase in brightness temperature at the spot in question is no greater than the expected increase in the brightness temperatures for a wet as opposed to a dry surface.

(iii) If a region is a thermogram exhibits a temperature of $0^{o}C$ after the correct temperature distribution on the thermogram has been established, and if the surrounding areas of the roof are colder, the region will probably correlate with standing water in a daytime aerial photo and if it does it can be interpreted as a two-phase system of partially-frozen water and ice.

6.2 The Comparative Analysis of the 1977 and 1978 Sites

The following conclusions have been drawn from the heat-loss analysis of the thermogram for two successive years:

(i) The temperature pattern of a roof is stable from one year to the next if the interior usage of the building is not changed. Radiant temperature variations in the order of a degree can be expected to be reproduced from one heating season to the next if the infrared data is acquired under reasonably similar conditions.

(ii) Changes in the interior usage of the top floor of a building are readily detected in a comparison of aerial thermograms.

(iii) Changes in the thermal performance of a roof due to repairs having been made can be identified through comparison of "before-and-after" thermograms. The radiant temperature of a roof that has been re-insulated to a better insulation standard has been observed in the present study to drop 2 Centigrade degrees.

(iv) The thermal pattern of the roof of a flat-roofed building that has a ventilated space between the inside (warm) ceiling and the outside roof deck will be more sensitive to wind direction and wind veloity than the pattern for an ordinary flat roof.

(v) In setting out the temperature pattern for a flat-roof from a thermogram, any bias in the overall radiant temperature that is introduced through calibration or processing can be largely removed by comparing the apparent radiant temperature of a high emissivity, isolated, surface such as clean snow with the local air temperature. These two temperatures should correspond reasonably well. If they do not the radiant temperatures on the thermograms can be adjusted up or down to bring them into reasonable agreement, say within 1 degree (C).

(vi) From a statistical point of view, many of the warm regions on a roof that coincide with water or ice, or both, are not warm because of excess heat loss through the roof. They are warm because the water or ice has simply not cooled to the temperature of the surrounding surface by the time the thermography is taken (typically between 9:00 P.M. and midnight). Standing water is slower to cool because of its heat capacity and the need to release latent heat of freezing to the local environment during the transition from the water to the ice phase.

(vii) With a procedure available by which the correct temperature distribution across wet and dry regions on a roof can be established, the limiting factor in assessing the probability of excess heat-loss at these spots reduces to deciding whether a warm, wet (or frozen) areas is being kept warm by anomalous heat loss from below or is simply cooling more slowly than the surrounding dry regions because of higher heat capacity. To put it another way, the interpreter must decide whether or not sufficient time has elapsed since sunset to permit all surfaces to come to equilibrium. If this condition has, in fact, occured the temperature pattern on a roof can be related directly to the heat loss pattern.

(viii) Heat-loss analysis of thermograms of flat roofs with patches of standing water is still a subjective undertaking unless an interpreter is reasonably certain the thermography is taken after all wet patches have come to final equilibrium with the surrounding environment. The availability of a method for determining the correct temperature distribution across the roof removes the first obstacle to interpretation - ambiguities as to whether a region is actually "warm" or is simply, radiantly speaking, "brighter". Thus the door to further analysis is opened and the interpreter can use judgement in assessing the cause of the warm areas. However, extensive research at the site is needed to confirm an analysis and there will be instances where confirmation can only be obtained through some other form of test - for example examination of suspect areas with a hand-held radiometer when the roof has dried off.

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6.3 General Conclusions

(i) It is commonly accepted that below-freezing temperature is an important conditon for collecting aerial thermographs. In view of the problems encountered with partially-frozen water, the relative importance of this below-freezing criterion should be re-examined.

(ii) The sky temperature during the experiment described in this report was such that the effects of the difference in emissivity between wet and dry surfaces, although present, was largely offset by the compensating effect of reflected sky radiation. These conditions were present to some degree in the 1977 experiment also. A small change in this difference, to either make it larger or smaller would not have a drastic effect on the present results, given the relative warm of the sky. In the currently available literature there is no well-documented instance of a wet and a dry surface both at the same temperature, exhibiting substantially different radiation temperatures under clear, cold-sky conditions. The actual difference in emissivity between wet and dry gravel when averaged over the 8-14 micron band may be less therefore than has been assumed thus far. In light of this uncertainty, some simple measurements with a portable radiometer over a wet and dry surface under a cold night sky would be a logical approach to obtaining a closer esimate of the emissivity variation. If it should turn out that the emissivity difference between a wet and dry roof is small - in the order of 2%, say - it would not be worth going to the trouble of carrying out a flooding exercise before collecting the aerial data. A "standard" compensation of, say , $1/2^{o}C$ or whatever was appropriate could be used and would be quite adequate for visual interpretation such as was used in the current study.

7. Recommendations

1. For future thermography projects we recommend a simple procedure which, if followed, will show in an aerial thermogram the net combined effect of emissivity and sky temperature on the radiant "temperature" of dry, wet, and frozen surfaces. With this information correct temperature distributions on roofs can be determined. The procedure is as follows:

(i) A large flat roof of conventional design is to be pre-selected and two large, separated areas chosen. Each area should be sufficiently large - 15 x 30 metres - to cover several scan lines in a resultant thermograph. On the day of the flight half of each area is sprayed with water; care must be taken to keep the other half dry. Puddles of standing water should be kept dispersed with brooms.

(ii) This procedure must be carried out several hours before the time of the night flight to allow complete freezing and final equilibrium. If the day flight is to be done the same day, the spraying should be delayed until the day flight is over.

(iii) When the data from the flight has been processed the radiant temperature variation between the wet and dry surfaces is to be noted and used to correct the apparent temperature differences of the other wet and dry surfaces in the data set.

(iv) Using this technique, reliable temperature profiles to an accuracy of approximately $\pm$ 1/2^{o}C can be prepared for subsequent interpretation.

2. We recommend that a thermography experiment be done at a temperature above freezing on a control roof containing wet and dry patches. If a satisfactory heat-loss analysis could be done with the thermograms produced by such an experiment two advantages would accrue. First, the water/ice interpretation for surfaces at 0^{o}C would be avoided as this pause in temperature drop until the system freezes completely would not occur. Second, in the spring of the year, by the time the normal ambient night-time temperature has risen above the freezing point, more of the remains of the winter's snow will be dried off and the flat roofs should in general be drier.

A disadvantage to this procedure is the loss of thermal stress across the roof because of closer inside and outside temperatures. No comparative quantitative data exists on the relative importance of this loss so it cannot be assumed to be of over-riding importance vis-a-vis the importance of having dry roofs when setting out the conditions under which the data is to be collected.

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