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# AIRBORNE THERMOGRAPHY OF TEMPERATURE PATTERNS IN SUGAR BEET PILES

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Remote Sensing Institute  
South Dakota State University  
Brookings, South Dakota 57006

May 1975



September 8, 1975

Mr. Herbert S. Snyder  
Grants Officer  
National Aeronautics & Space Administration  
Washington, D.C. 20546

Dear Mr. Snyder:

I am enclosing 5 copies of a report entitled "Airborne Thermography of Temperature Patterns in Sugar Beet Piles," describing work that is credited to the NASA Office of University Affairs Program.

Sincerely yours,

A handwritten signature in cursive script, appearing to read "Victor I. Myers".

VICTOR I. MYERS  
Director

VIM/ss  
Enclosures

## ABSTRACT

## Airborne Thermography of Temperature Patterns in Sugar Beet Piles

by

Donald G. Moore and Stanley Bichsel <sup>1/</sup>

Spoilage of sugar beets stored in piles can cause substantial financial loss to the processor and grower. The generation of heat within the pile due to the spoilage process is normally expressed as a temperature anomaly. A procedure using contact temperature measurements for locating the spoilage areas requires that a large quantity of temperature measuring devices be implanted in the pile with only moderate success. Since a large portion of the heat is transferred vertically, monitoring the surface emittance of the pile with airborne thermography may be a method of locating the spoilage areas. An investigation with funding provided jointly by the American Crystal Sugar Company, the State of South Dakota, and the National Aeronautics and Space Administration Office of Education Grant Number NGL 42-003-007 was pursued by personnel of the Remote Sensing Institute and the American Crystal Sugar Company to evaluate the use of thermography for locating spoilage areas (chimneys) within storage piles and to subsequently use the information for the scheduling of their processing.

Thermal-infrared (8.7-11.5  $\mu\text{m}$ ) quantitative scanner data were acquired initially on January 16, 1975, over the storage piles at Moorhead, Minnesota, both during the day and predawn. Photographic data were acquired during the day mission to evaluate the effect of uneven snow cover on the thermal emittance. The predawn thermography was used to locate potential chimneys. The piles were examined the day prior for indications of spoilage areas. The ground crew indicated that no spoilage areas were located using their existing methods. Nine spoilage areas were interpreted from the thermography. The piles were rechecked by ground methods three days following the flights. Six of the nine areas delineated by thermography were actual spoilage areas. A second set of daytime-predawn missions was scheduled for the Moorhead piles on February 18, 1975. Nine additional storage sites in North Dakota and Minnesota were included for this second mission. As in the January mission, field evaluations revealed that the technique was usable for locating spoilage areas.

When spoilage areas are located in early season, the piles are sectioned for processing according to the distribution of these spoilage areas. In the late processing season, the piles are scheduled according to those with the greatest spoilage. The American Crystal Sugar Company is presently planning to use thermography for scheduling pile processing as an operational procedure for the next harvesting season.

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<sup>1/</sup> Research Soil Scientist, Remote Sensing Institute; and Vice President of Research, American Crystal Sugar Company; respectively.

## TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT . . . . .	i
TABLE OF CONTENTS . . . . .	ii
LIST OF FIGURES . . . . .	iii
INTRODUCTION . . . . .	1
ABOUT THERMOGRAPHY . . . . .	2
Radiation . . . . .	2
Thermal Scanner Operation . . . . .	3
Characteristics of Scanner Used for Data Collection . . . . .	4
DATA COLLECTION . . . . .	5
DATA COLLECTION AND EXAMPLE PRODUCTS . . . . .	5
January . . . . .	5
February . . . . .	6
SUMMARY AND RECOMMENDATIONS . . . . .	7

## LIST OF FIGURES

<u>FIGURE</u>		<u>PAGE</u>
1	Schematic illustration of scanner operations from data collection to product generation . . . .	10
2	Photographic print illustrating the irregular snow distribution on piles at Moorhead site on 16 January 75 . . . . .	11
3	A six gray-level thermogram of Moorhead site acquired 01:32 CST on 16 January 75 . . . . .	12
4	Apparent temperatures from -9.17 C to -8 C thematically extracted from thermogram in Fig. 3 . . . . .	13
5	Photographic print illustrating the irregular snow distribution on pile at Moorhead site on 18 February 75 . . . . .	14
6	A six gray-level thermogram of Moorhead site acquired 22:41 CST on 18 February 75 . . . . .	15
7	Digitally processed predawn thermogram comparable to image presented in Fig. 6 . . . . .	16

## AIRBORNE THERMOGRAPHY OF TEMPERATURE PATTERNS IN SUGAR BEET PILES<sup>1</sup>

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### INTRODUCTION

Spoilage of sugar beets in storage piles can cause substantial financial loss to the processor and grower. Sugar beet spoilage results in the generation of heat within the pile which is normally expressed as a temperature anomaly. Therefore, temperature monitoring of the storage pile is a method for detecting spoilage areas. A procedure using contact temperature measurements within the pile requires a large quantity of temperature measuring devices to be implemented in the pile with only moderate success of detecting the spoilage areas.

Since a large portion of the heat generated by spoilage is transferred vertically via convection (in addition to conduction and radiation), a temperature difference in the beets above the spoilage area may occur at or near the surface of the pile over the resulting chimney. Airborne thermal-infrared scanner imagery (thermography) may, therefore, provide a method of rapidly locating these spoilage areas.

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<sup>1</sup> RSI-SDSU-J-75-05. Funding provided jointly by American Crystal Sugar Company, State of South Dakota, and National Aeronautics and Space Administration Office of Education Grant Number #NGL 42-003-007.

An effort to evaluate the use of thermography to locate spoilage areas and aid in scheduling the processing of sugar beet piles was pursued. The activity was jointly funded by the American Crystal Sugar Company, the State of South Dakota, and the National Aeronautics and Space Administration Office of Education Grant Number #NGL 42-003-007.

## ABOUT THERMOGRAPHY

### Radiation

The use of electronic scanners allows the remote sensor to record energy in the thermal region of the electromagnetic spectrum. This thermal region is in addition to those spectral regions which have been traditionally recorded using photography. The presently available photographic materials have sensitivities which can capture electromagnetic energies only to approximately 0.9  $\mu\text{m}$ . The lower energy levels of the thermal portion of the spectrum (generally referred to as from 4 - 50  $\mu\text{m}$ ) must therefore be measured and recorded by electronic systems in contrast to measurement by photographic systems.

Every body with a temperature above that of absolute zero radiates energy. An estimate of the energy radiated is given by the Stefan-Boltzmann Law:

$$\text{Heat flux (I)} = \epsilon \sigma T^4$$

where  $\epsilon$  is the emissivity (or one minus the infrared albedo)  
 $\sigma$  is the Stefan-Boltzmann constant  
 and  $T$  is the absolute temperature of the radiating object.

For a perfect blackbody radiator, the  $\epsilon$  is unity. The radiating surfaces of the earth are termed "gray bodies" and radiate with an emissivity less than unity.

The surface of the earth averages approximately 285 degrees Kelvin. According to Wien's displacement law, the wavelength of maximum intensity is inversely proportional to the absolute temperature ( $T$ ) or:

$$\lambda_{(\text{max})} = 2897 T^{-1}$$

where  $\lambda_{(\text{max})}$  is the wavelength of maximum intensity in  $\mu\text{m}$   
 and  $T$  is the absolute temperature in degrees Kelvin.

The 285 degrees Kelvin therefore corresponds to approximately 10  $\mu\text{m}$ .

If a non-contact or remote-sensing sensor is used to quantitatively measure the emitted radiation, by definition the emitted energy must travel from the radiating source to the detector. The alteration of the energy in transit can be serious in certain portions of the thermal spectrum. For example, the principle atmospheric absorbers in the thermal region include water vapor from 5.3  $\rightarrow$  7.7  $\mu\text{m}$  and beyond 20  $\mu\text{m}$ , ozone from 9.4  $\rightarrow$  9.8  $\mu\text{m}$ , and carbon dioxide from 13.1  $\rightarrow$  16.9  $\mu\text{m}$ <sup>1</sup>. Clouds absorb in all thermal wavelengths. In cloud-free atmospheres, thermal regions such as 4.0  $\rightarrow$  5.3  $\mu\text{m}$ , 7.7  $\rightarrow$  9.4  $\mu\text{m}$ , or 9.8  $\rightarrow$  13.1  $\mu\text{m}$  are termed "windows". These windows are the appropriate spectral regions for remotely monitoring scene emittance with a minimum of atmospheric influence.

Since the wavelength of maximum intensity for the earth is approximately 10  $\mu\text{m}$  and this occurs within a window, this spectral region is normally chosen for sensor design. The atmospheric transmission is not totally without energy alteration from the radiating surface and the emissivities of the radiating surfaces are not unity. Therefore, the emittance as measured by the remote sensor and internally calibrated to temperature by comparing to a known source of radiation is not a true temperature but is termed "apparent temperature".

### Thermal Scanner Operation

A thermal-scanning system is used to convert the land surface emittance as viewed with a detector and recorded electronically into an image which can be used for interpretation. A generalized diagram of a typical system is provided in Fig. 1. Forward motion of the aircraft and rotation of the mirror produce a series of data lines which can be reassembled into an image similar to a traditional photographic image. The actual data recorded are voltages whose amplitudes are

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<sup>1</sup> Sellers, W.D. 1965. Physical Climatology. The University of Chicago Press, Chicago, Illinois.

proportional to the incoming energy levels. The instantaneous field of view, spectral sensitivity, thermal resolution, detector response time, etc., are all system properties which vary from scanner to scanner.

Operating parameters such as adjustment of blackbody references and determination of the appropriate V/H (Velocity to Height ratio) of the aircraft are operator controlled. Certain scanners have internal blackbodies which are used to relate the input energy to output voltages. The incoming radiation signals are alternately compared with known energy reference sources. These known energy references are adjusted to bracket the anticipated energy level of the radiating surface being measured. A comparison of these known energy levels to the measured levels allows the interpreter to determine quantitatively the incoming energy levels with subsequent calibration to equivalent blackbody temperatures. Since the scanner mirror rotates at a constant speed and has a fixed geometry, the V/H must be determined and adjusted to relate aircraft motion with film speed during processing to produce continuous, near-rectilinear coverage of the land surface in the resultant image.

#### Characteristics of Scanner Used for Data Collection

A trimetal (Hg:Cd:Te) detector cooled to liquid nitrogen temperatures was used to detect the incoming thermal radiation. The spatial resolution of the Daedalus scanner is 1.7 milliradian. As a function of aircraft altitude, this corresponds to 0.52-m (1.7 ft) resolution cell per 305 m (1000 ft) of aircraft altitude. The spectral response of the filtered signal and the detector is approximately 8.7 - 11.5  $\mu\text{m}$ . The operational range of the analog voltage signal is from +1.8 - -1.8 volts. These voltage extremes are used for the blackbody settings which are adjustable and can be determined by viewing the range of signal on an oscilloscope for the terrain to be recorded. These adjustments normally require a preliminary aircraft pass over the area to be imaged for determination of the appropriate blackbody settings. The thermal resolution of the system is

approximately 0.2 degrees Celsius (C) with the absolute accuracy of the blackbodies quoted at  $\pm 0.5$  C.

### DATA COLLECTION

Past experience in acquiring thermal data has established the following general guides for data collection. Predawn data collection minimizes the effects of surface temperature fluctuations associated with the incoming daytime solar radiation. At least 3 to 4 hours should be allowed after sunset prior to data collection to further reduce these effects. Atmospheric and land surface conditions should be such that phase changes of water, such as dew or frost formation, are not occurring. Three to four days should be allowed after a rainfall to establish a temperature environment not dependent upon the movement of water but dependent upon the heat transfer characteristics of the specific materials to be tested. Surface winds no greater than 10 knots should be tolerated with improved results as the surface winds continue to diminish.

These guides were followed in scheduling thermal flights over the beet storage site at the American Crystal Sugar factory at Moorhead, Minnesota. Both daytime and predawn flights were scheduled for 16 January 1975 and 18 February 1975. Both photographic and thermal-scanner data were acquired for the day flights and only thermal-scanner data were acquired for the predawn flights.

### DATA COLLECTION AND EXAMPLE PRODUCTS

#### January

The sugar beet piles were partially covered with snow as illustrated in the photographic image in Fig. 2 acquired 16 January 1975. The uneven topography on the surface of the pile in conjunction with the prevailing winds probably caused this snow-cover distribution. The imagery was exposed late in the afternoon in January which accounts

for the extreme shadowing caused by low sun angles. Thermal data were acquired at 01:32 CST at 366-m (1200 ft) above ground level (AGL) and a resultant print with gray tones representing input energies is included in Fig. 3. The blackbodies were adjusted to  $-15^{\circ}\text{C}$  and  $-8^{\circ}\text{C}$ . The air temperature at 366-m (1200 ft) AGL was  $-8^{\circ}\text{C}$  at the time of overflight. Surface winds were calm under a clear sky.

The blackbody adjustments were determined by overflying the piles and observing the signal amplitude of the processing plant, roads and structures, piles, and other scene features. Because of the small size of the hotter spots within the piles, an accurate reading could not be adequately determined for the adjustment of the blackbodies to assure inclusion of the pile hot spots within the blackbody range. The pile hot spots were the hottest objects in the total scene. Light spots in the print in Fig. 4 represent the warmest apparent temperatures of the scene presented in Fig. 3 which range from  $-9.2^{\circ}\text{C}$  to  $-8^{\circ}\text{C}$  and warmer. A further analysis of these data to determine which of these spots were the warmest was not possible because the upper blackbody level chosen was not as warm as it should have been to include the maximum temperature of the pile surfaces.

The predawn thermography was used to locate potential chimneys by interpreting those apparent temperatures which were spatially within the center two thirds of the pile and were the warmest apparent temperatures in the scene. The piles were examined the day prior to aerial data collection for indications of spoilage areas. The ground crew indicated that no spoilage areas were present. Nine locations of potential spoilage areas were interpreted from the thermography. The piles were rechecked by ground methods three days following the flight. Six of the nine areas delineated by thermography were actual spoilage areas.

### February

The piles were partially snow covered as illustrated in the photographic image in Fig. 5. Predawn thermal data were acquired at 22:41 CST on 18 February 1975. The thermal data are presented in Fig. 6. The blackbodies were adjusted to  $-14^{\circ}\text{C}$  and  $+6^{\circ}\text{C}$  for this flight.

The air temperature at 366-m (1200 ft) AGL was -5 C at the time of the flight. The surface winds were blowing from 190 degrees at 16 km/hr (10 mi/hr). The output in Fig. 7 is an overstrike computer printout resulting from digitizing the original analog tape into 256 levels. These levels were calibrated using the blackbody references and level sliced into nine separate levels which enhanced the ability to separate the snow-covered and non-snow-covered areas of the piles and apparent emittances within each.

Nine additional storage sites in North Dakota and Minnesota were included for this second mission. As in the January mission, field evaluations revealed that the technique was usable for locating spoilage areas.

#### SUMMARY AND RECOMMENDATIONS

The technique of using airborne thermography to detect chimneys associated with spoilage areas in sugar beet storage piles appears to have promise. Similar results have been obtained in a study of non-snow covered piles in Colorado (personal communication from Mr. Sherman Fox<sup>1</sup>). The advantages of using this technique over contact temperature monitoring devices are obvious. The results of the preliminary feasibility study do provide information on the applicability of thermography for the limited conditions studied.

The quality of the instrumentation, selection of flight parameters, and operator expertise are critical. Temperature resolution of at least 1 C would be minimal for the data analyzed in this effort. In zones where fall and winter climates are not as extreme in air temperature fluctuations as in this northern latitude test site, even greater instrument temperature resolution may be required. The instantaneous field of view of the scanning system will primarily determine the aircraft altitude required to assure spatial resolution adequate to detect small hot spots. For example, these data were acquired at 366-m (1200 ft) AGL with a 1.7 milliradian detector.

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<sup>1</sup> Sherman Fox; Great Western Sugar Company, Agricultural Research Center, Longmont, Colorado; reference to unpublished report.

The instantaneous field of view at this altitude is  $\approx 0.62$  m (2.0 ft). This spatial resolution was sufficient. Flights at considerably lower altitudes to obtain higher spatial resolution are difficult to schedule because of crew safety factors. In addition, the total width of scan with the system used was  $\approx 586$  m (1920 ft) at 366-m (1200 ft) AGL which was adequate to image the piles in the processing plants with one flight line even when the navigation was not exact. Navigation of predawn flight lines without expensive navigation equipment but by visual recognition is difficult in some areas. Therefore, a wide scan swath is fully appreciated.

The imagery product (as in Fig. 6) is less desirable than the digital product (as in Fig. 7). Therefore, these authors recommend the digital processing technique. Color encoding of data products normally does not improve the interpretation sufficiently to warrant the additional costs. The method for data reduction and interpretation is important both for reliability of the product and timeliness of delivery of results. Interpreting either by the imagery or digital technique must allow rapid completion of the survey. For both dates of this investigation, the products and interpretations were delivered within three days following the data acquisition. For the January date, the photographic product was available on site by noon on the day following the predawn data acquisition.

Continued research is required before the technique can become fully operational to produce reliable interpretations for all geographic locations for all times without considerable ground verification. Such research includes:

1. Determine emissivity variations in scenes of interest.
2. Develop a model predicting the relationship of surface temperatures with time for areas over chimneys and normal beets for diurnal and seasonal cycles.
3. Continue to develop operational techniques for adjusting blackbody and other scanner parameters.
4. Field evaluate methods for data reduction and interpretation.

5. Field evaluate methods under varying environmental conditions with critical ground verification.
6. Provide cost/benefit analysis for an actual "operational" system.

The American Crystal Sugar Company feels that the techniques, even without extensive refinement, will provide a favorable cost/benefit ratio and is planning at least three thermography missions for various storage sites in North Dakota and Minnesota during the following season. From the February data provided for the Moorhead site during this investigation, pile rescheduling for processing was conducted. The yard manager concluded that the rescheduling activity minimized total spoilage during the completion of processing of the two remaining piles at Moorhead (personal communication; Stewart Bass, American Crystal Sugar Company, Moorhead, Minnesota).

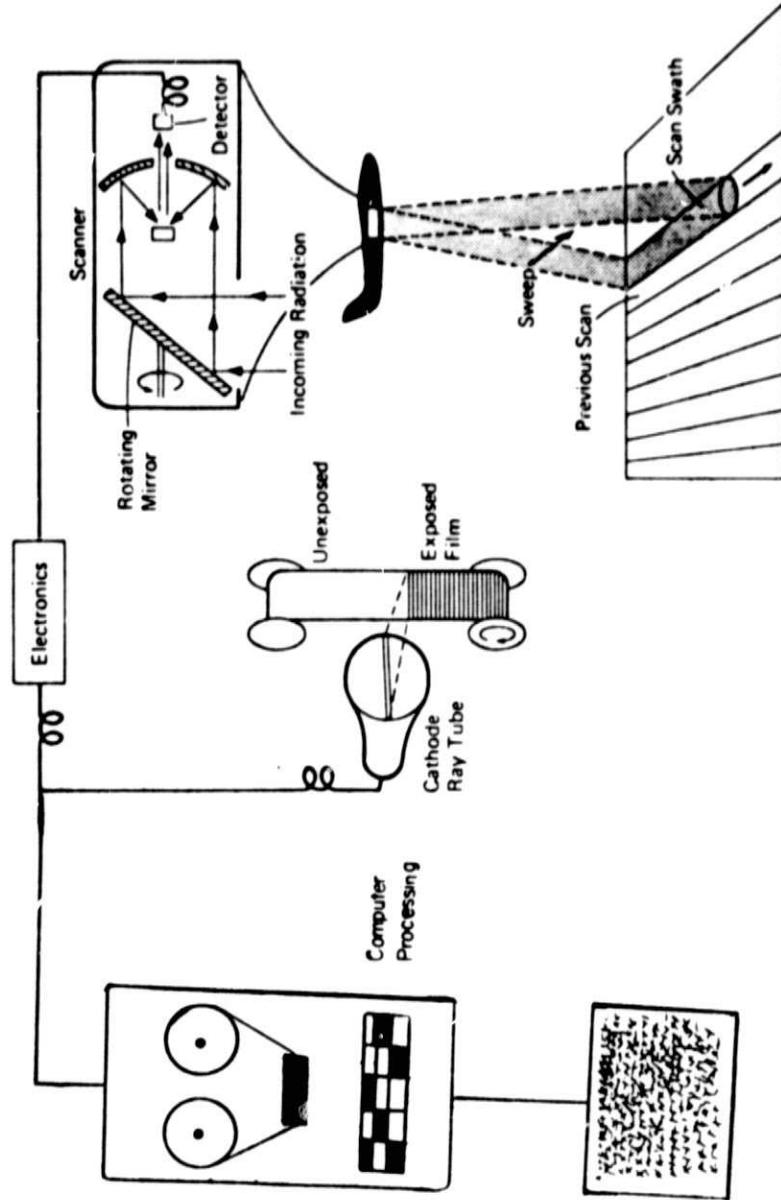


Fig. 1 - Schematic illustration of scanner operations from data collection to product generation.



Fig. 2 - Photographic print illustrating the irregular snow distribution on piles at Moorhead site on 16 January 75. Extreme shadowing is caused by low sun angles. Approximate scale is 1:1800.

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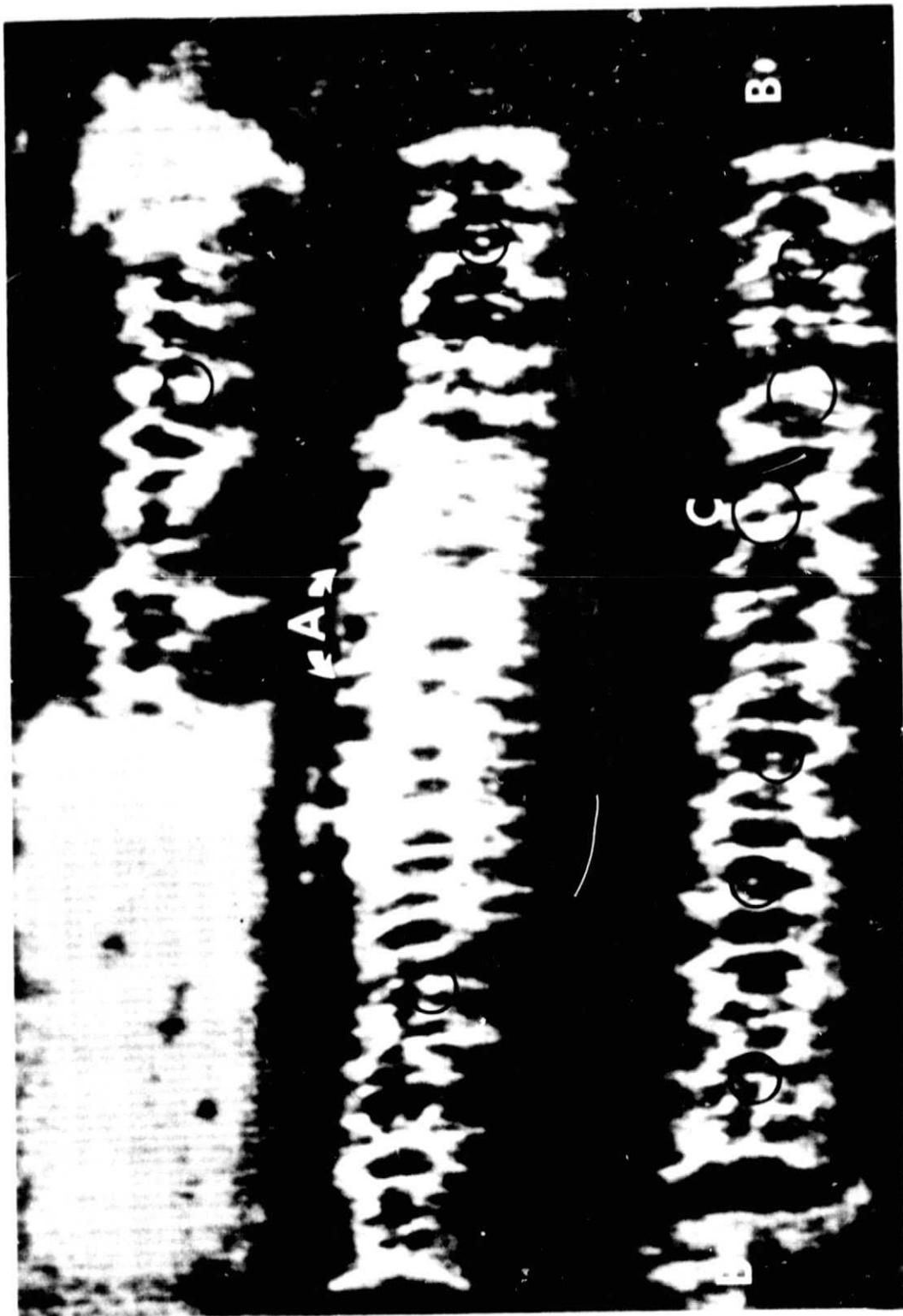


Fig. 3 - A six gray-level thermogram of Moorhead site acquired 01:32 CST on 16 January 75. Light is warm with apparent temperatures ranging from -8 C to -15 C. Arrows at "A" point to warm areas of piles associated with warm-air exhaust from fans flushing cool air through piles. The letter "B" denotes combusting charcoal in containers. The circles denote areas of probable chimneys. The circle at "C" is the similar area to those labeled "C" in Figs. 5, 6, and 7.

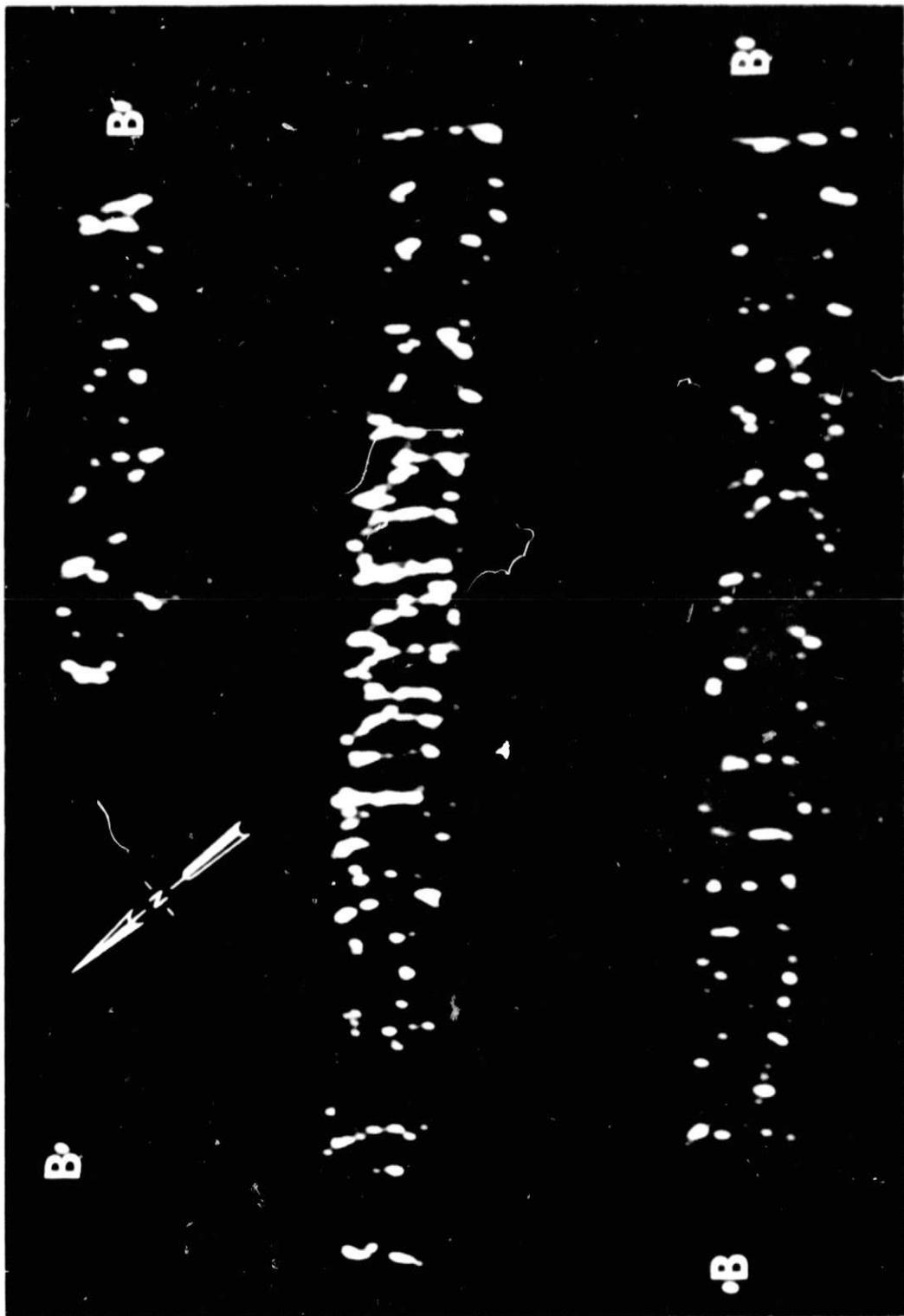


Fig. 4 - Apparent temperatures from -9.17 f to -8.0 theratically extracted from thermogram in Fig. 3. The warm-end temperatures are light on the image. Charcoal grills are at "B" locations.

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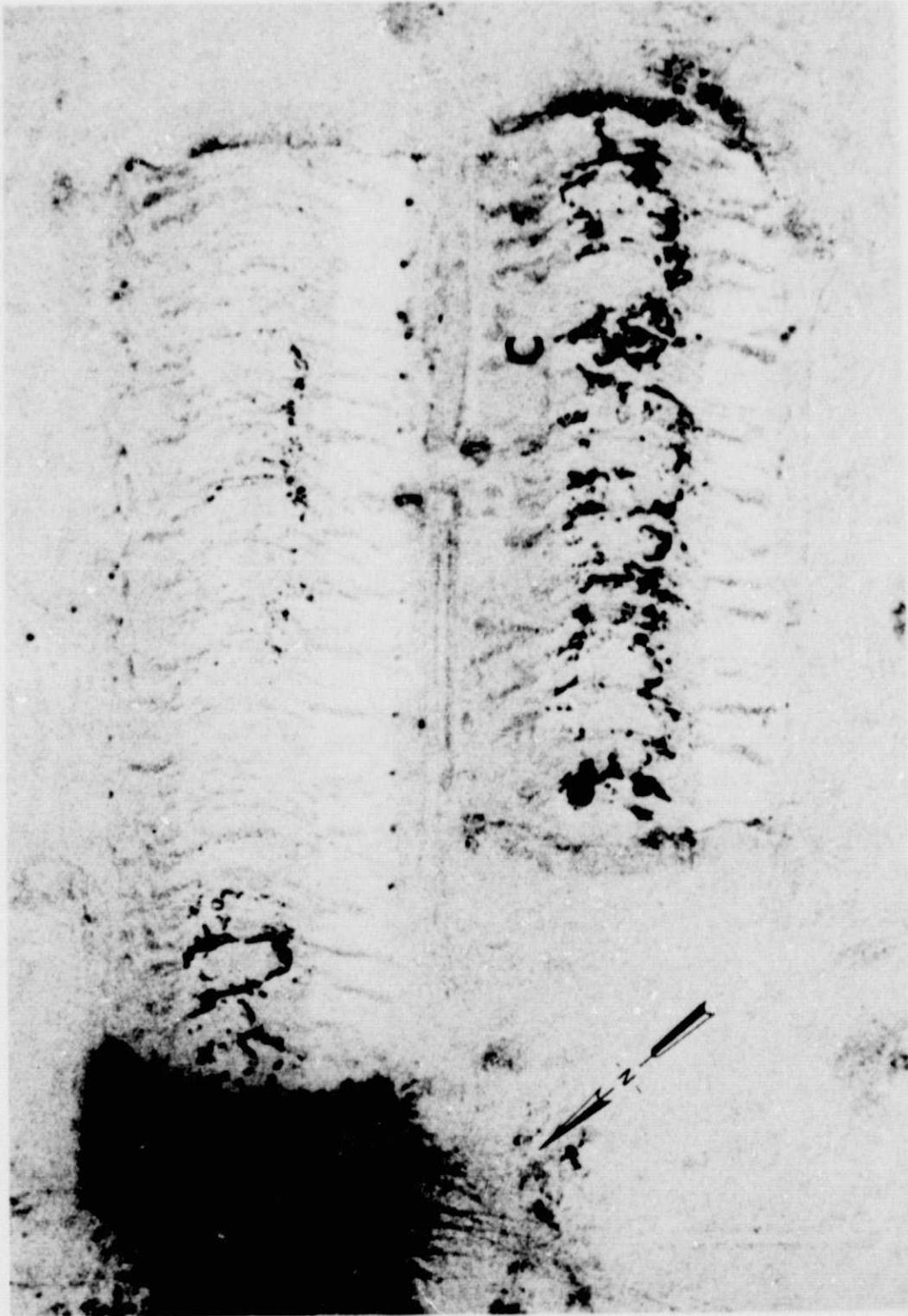


Fig. 5 - Photographic print illustrating the irregular snow distribution on piles at Moorhead site on 18 February 75. Approximate scale is 1:1000. "C" denotes similar area as in Figs. 3, 6, and 7.

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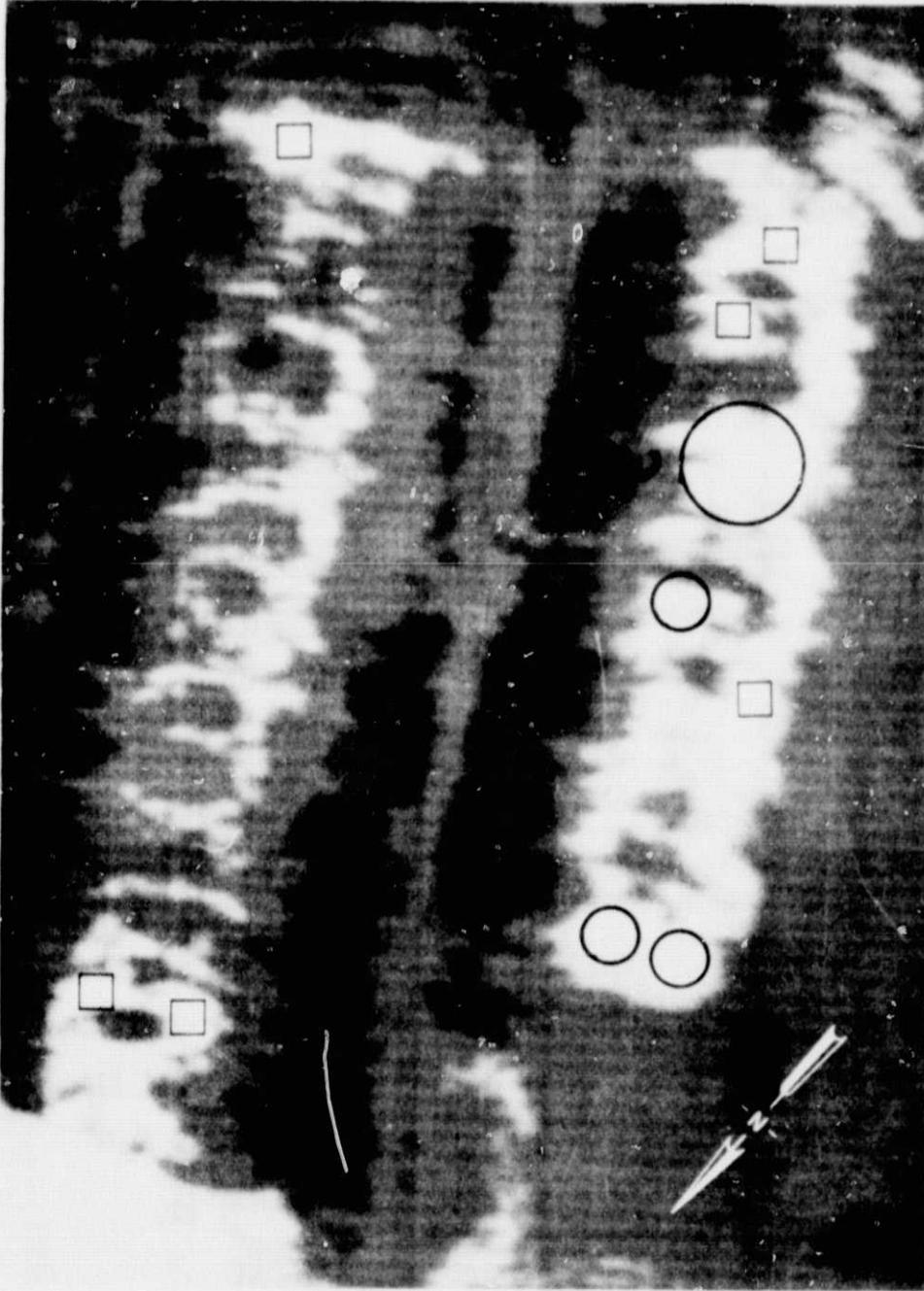


Fig. 6 - A six gray-level thermogram of Moorhead site acquired 22:41 CST on 18 February 75. Light is warm and the total apparent temperature range is -14 C to +6 C. Circled areas are the warmest and are probable chimneys as determined by interpreting a level slice image similar to that in Fig. 4. Areas enclosed by squares are "likely" chimneys but were not in the warmest extreme of apparent temperatures. Note the increase in size of area "C" from the 16 January 75 thermography in Fig. 3.

# Sugar Beet Piles

PREDAWN - THERMAL 2-18-75

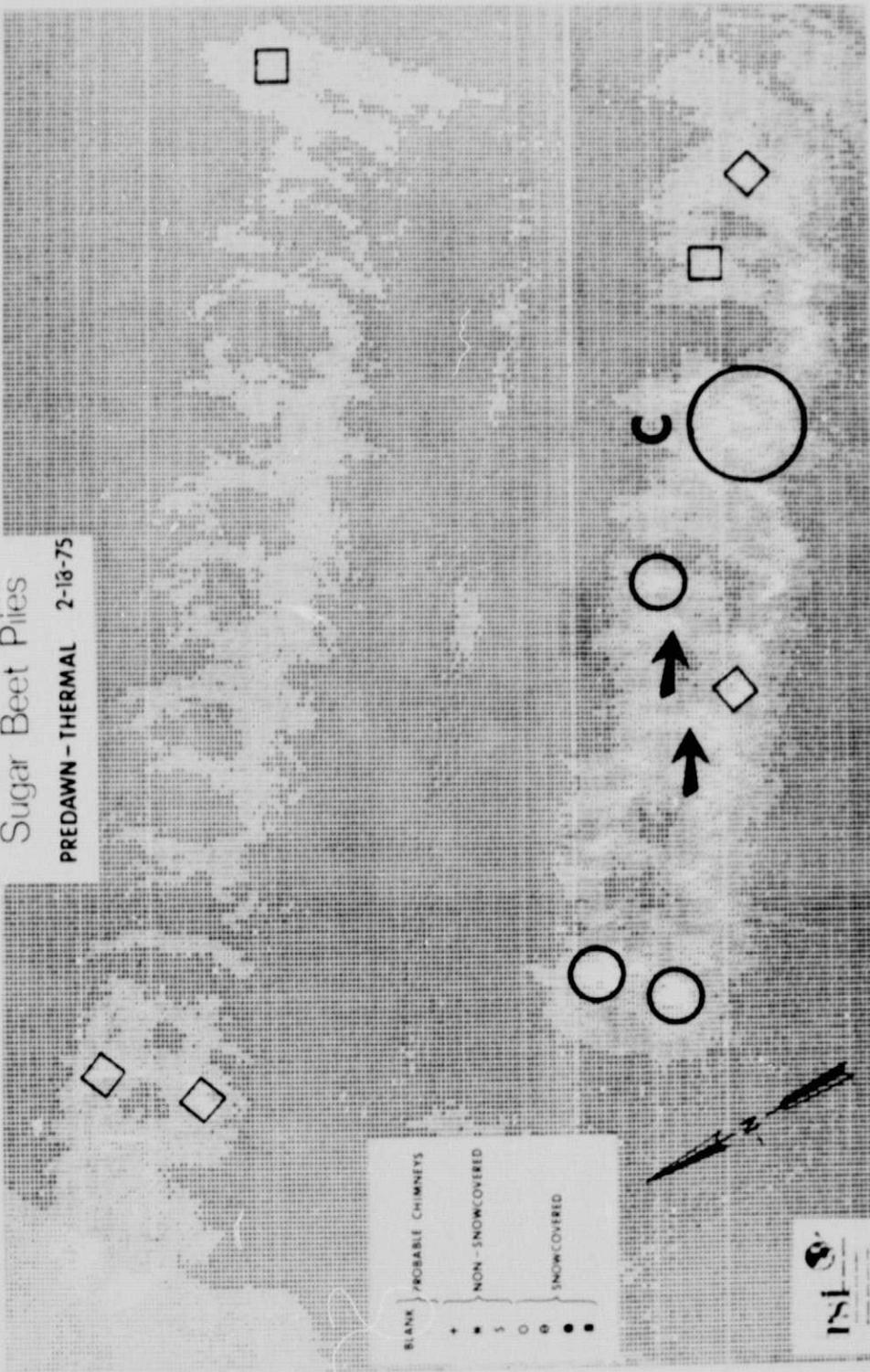


Fig. 7 - Digitally processed pre-dawn thermogram comparable to image presented in Fig. 6. Circled areas are those interpreted both from data in Fig. 6 and these digital data. Areas denoted by diamonds are those interpreted as probable chimneys from these digital data and as "likely" chimneys in Fig. 6. Areas enclosed by squares are areas interpreted as probable or likely chimneys in Fig. 6 and not indicated as probable chimneys in these data. Arrows point to two of many additional probable chimneys in data when they are critically analyzed using these digital techniques. Equivalent blackbody temperatures are: "blank" +6.0 - -1.0 C; "■" -1.0 - -1.9 C; "+" -3.9 - -3.9 C; "S" -4.5 - -4.5 C; "O" -5.5 - -5.5 C; "Q" -6.4 - -6.4 C; "θ" -7.4 - -7.4 C; "8" -8.1 - -14.0 C.

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