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CRREL REPORT 76-33

Detecting structural heat losses with mobile infrared thermography

Part IV: Estimating quantitative heat loss at Dartmouth College, Hanover, New Hampshire

Cover: Thermogram and photograph of Woodbury Hall, taken on 28 March 1974. Arrows point to heat loss from radiator conducted through brick wall.

CRREL Report 76-33

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Detecting structural heat losses with mobile infrared thermography

Part IV: Estimating quantitative heat loss at Dartmouth College, Hanover, New Hampshire

R.H. Munis, S.J. Marshall and M.A. Bush

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CORPS OF ENGINEERS, U.S. ARMY
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During the winter of 1973-74 a mobile infrared thermography system was used to survey campus buildings at Dartmouth College, Hanover, New Hampshire. This report provides both qualitative and quantitative data regarding heat flow through a small area of a wall of one brick dormitory building before and after installation of aluminum reflectors between radiators and the wall. These data were used to estimate annual cost savings for 22 buildings of similar construction having aluminum reflectors installed behind 1100 radiators. The data were then compared with the actual savings which were calculated from condensate meter data. The discrepancy between estimated and actual annual cost savings is explained in detail along with all assumptions required for these calculations.

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PREFACE

This report was prepared by Dr. Richard H. Munis, Research Physicist, Stephen J. Marshall, Physical Science Technician, and Michael A. Bush, Physical Science Aid, of the Physical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

The study was conducted under DA Project 4A161101A91D; Task 03, *In-House Laboratory Independent Research*; Work Unit 174, *Thermal Radiation.*

This report was technically reviewed by Dr. Y.C. Yen and R.H. Berger of CRREL.

The authors wish to thank Richard Plummer, Director of Buildings and Grounds, Dartmouth College, for providing the personnel, data, technical information, and necessary facilities for completion of this project. The authors also wish to thank Dr. Y.C. Yen and R.H. Berger for their suggestions regarding the discussion on the calculation of heat flow.

CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4*	millimeter
foot	0.3048*	meter
$foot^2$	0.09290304*	$meter^2$
mile/hour	0.44704*	meter/second
pound-mass	0.4535924	kilogram
Btu/hour	0.2930711	watt
Btu/h ft^2 °F	5.678263	W/m^2 K
degrees Fahrenheit	$t^\circ_C = (t^\circ_F - 32)/1.8$	degrees Celsius

* Exact

DETECTING STRUCTURAL HEAT LOSSES WITH MOBILE INFRARED THERMOGRAPHY
Part IV: Estimating Quantitative Heat Loss at Dartmouth College, Hanover, New Hampshire

R.H. Munis, S.J. Marshall and M.A. Bush

INTRODUCTION

During the winter of 1973-74, the U.S. Army Cold Regions Research and Engineering Laboratory developed a survey technique to detect heat losses by using an infrared scanner. A mobile infrared scanner system was leased from the Barnes Engineering Company of Stamford, Connecticut, and heat loss surveys were made of CRREL, Pease Air Force Base, and the Dartmouth College campus. Part I of CRREL report based on these surveys (Munis et al. 1974)* gives a description of the technique, Part II (Munis et al. 1975)† gives the results of the survey of Pease Air Force Base, Portsmouth, New Hampshire, and Part III (Munis et al. 1975)** describes the results obtained from the survey of the CRREL building at Hanover, New Hampshire.

This report provides an estimate of quantitative heat losses of a dormitory building on the Dartmouth College campus derived by using the infrared scanner system, during the months of March and April 1974. The report also contains a qualitative evaluation of heat losses from the same dormitory building.

DISCUSSION

In the previous three reports we attempted to outline qualitative and some quantitative aspects of using infrared thermography to locate excessive heat losses in buildings. The increased usage of infrared scanners for inspecting buildings has led to wide-ranging discussions of whether or not thermography can be used effectively to obtain quantitative values of heat loss from buildings, and thereby to obtain cost savings by correcting locations of inadequate insulation. In order to provide some insight into this problem, we did a detailed study of one wall of a dormitory building (Woodbury Hall) on the campus of Dartmouth College at Hanover, New Hampshire (Fig. 1).

Before describing the process by which we derived cost savings from surface temperature measurements of the building wall, we will present a discussion of what information thermography can and cannot provide about the thermal integrity of a building. Later, we will demonstrate how thermographically measured surface temperatures can be used to calculate the approximate heat loss.

** Munis, R.H., R.H. Berger, S.J. Marshall and M.A. Bush (1974) Detecting structural heat losses with mobile infrared thermography, Part I: Description of technique. U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL) Research Report 326. ADA001549.*

† Munis, R.H., R.H. Berger, S.J. Marshall and M.A. Bush (1975) Detecting structural heat losses with mobile infrared thermography, Part II: Survey of Pease Air Force Base, Portsmouth, New Hampshire. USA CRREL Research Report 338. ADA012117.

*** Munis, R.H., R.H. Berger, S.J. Marshall and M.A. Bush (1975) Detecting structural heat losses with mobile infrared thermography, Part III: Survey of USA CRREL. USA CRREL Research Report 348. ADA020375.*

Figure 1. Woodbury Hall, Dartmouth College.

Information derived from thermograms

A thermogram of a heated (or air-conditioned) building yields a substantial range of qualitative information regarding the thermal condition of the structure. Since all of this information is contained in the shading or gray scale of a black and white photograph, it is sometimes difficult to sort out any one piece of information. However, this "sorting" must be done in order to provide an accurate thermal analysis of the structure.

Because an infrared scanner registers all heat emanating from a surface, a thermogram always shows the actual heat transfer characteristics of a building when the thermogram was taken.

For many reasons, few buildings are ever constructed exactly as they were designed. A drawing, for example, shows two masonry walls designed to make a 90° joint which allows no heat loss by infiltration. In practice, however, the joint is usually not "perfect" from top to bottom, and the deviation from "perfection" is revealed on a thermogram as heat loss (Fig. 2). The "imperfection" in this joint could have been introduced at the time of construction, or it could have been caused over the years by differential settling, cracking of the mortar, etc. This type of heat loss is known as *infiltration loss*.

An example of the difference between *design* and *actual* heat transfer characteristics revealed on thermographic images occurs when insulation is not installed properly in (or is omitted from) the spaces between wall studs in frame constructions. In a well constructed building, the insulation should be installed so that little or no heat escaping between the insulation and studs can be detected by the infrared scanner. However, as Figure 3 shows, the thermogram indicates an actual condition where heat *is* escaping.

Figures 2 and 3 show evidence of these heat losses. The thermogram of the building exterior shows a brighter shading in the locations where the construction defects occur than in the surrounding similar material. If obtained from the inside of the structure, the thermogram would show a darker shading in the locations where construction defects occur than in the surrounding similar material. However, any temperature information registered on a thermogram is a combination of the temperature of the surface material and the properties of the material. Therefore, all heat emanating from a surface is included in this temperature information.

Since all shades of gray are possible on a thermogram, an attempt to correctly interpret the thermogram is very difficult, if not impossible, without obtaining corresponding information on the characteristics of the surface from which the heat emanates. For example, a brighter spot at one location on a thermogram than at another may signify nothing more than a difference of emissivity due to a different type, or even a different color of the same type, of construction material at that location on the building surface.

Since it is possible to apply a multitude of explanations to various "gray shades" describing the heat transfer characteristics of a building, a definite requirement for successful interpretation of a thermographic

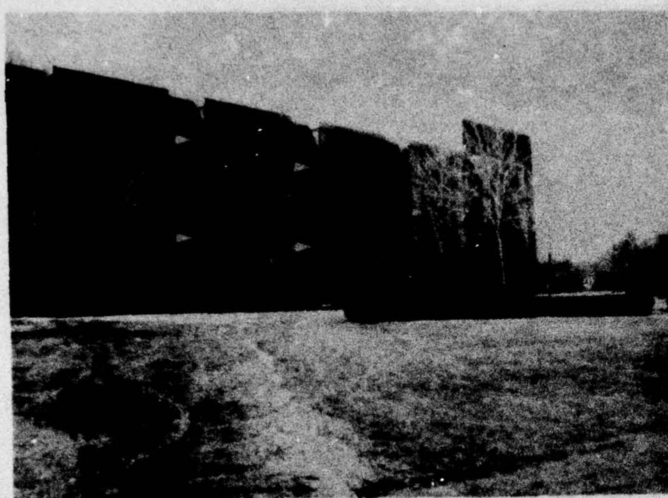

Figure 2a. Strasenburgh Hall on the Dartmouth College campus. White arrows point to construction joint between window frame and masonry.

Figure 2b. Thermogram of Strasenburgh Hall. Black arrows point to infiltration loss through construction joints shown in Figure 2a.

image is some experience or familiarity with techniques of construction and insulation, as well as with the physical layout of the interior and exterior of the building when the thermogram is taken. It is extremely important to remember that, with the current state of knowledge, it is very difficult to accurately evaluate quantitative differences in the heat transfer characteristics of a building. However, the immediate benefit to be gained by the use of infrared thermography is that it pinpoints locations of excessive heat loss or gain in heated and air-conditioned buildings. However, these locations can be correctly identified only if the information concerning techniques of construction and location and method of insulation installation is known.

The examples of heat loss mentioned previously can usually be regarded as unnecessary and wasteful. We believe that, by using infrared thermographic inspection techniques to pinpoint the locations of heat losses, construction and insulation defects can be located and corrected in present construction and avoided in future construction.

An infrared scanner system does not in itself yield information on the *rate of heat loss* from a location. If properly calibrated, it only indicates surface temperatures by providing a "map" of the surface when the infrared scanner operates in the isothermal mode. Since the infrared scanner system measures only a surface temperature distribution, it cannot produce by itself quantitative information on the thermal design characteristics of a building. Thus, for example, to thermographically derive the unknown thermal resistance of a wall (i.e., to determine if there were 2, 4, or 6 in. of insulation), it would be necessary to measure (under conditions of thermal equilibrium) both the inside and outside surface temperatures of

Figure 3. Arrows show heat escaping between insulation and 2-in. by 4-in. studs.

a wall whose insulation characteristics were already known.

Qualitative assessment of heat losses

The following is a description of the qualitative assessment of heat losses (obtained by using an infrared scanner system) from small segments of a brick dormitory building on the Dartmouth College campus.

Before any calculations could be attempted, reasonable values of the wall surface temperature had to be obtained. We accomplished this by simply getting an object whose temperature could be measured approximately into the field of view of the infrared scanner system. This object was either a tree, a pole, or the surface of the frozen ground (usually snow covered). We then measured the ambient air temperature near the object and assigned the result to the object. Next, by operating the infrared scanner system in the isothermal mode, we measured accurate temperature differences across the surface of the brick wall.

With a variety of prevailing ambient conditions (wind gusts and steep boundary-layer temperature gradients), and an assumption that the surface temperature of an object is approximately equal to the nearby air temperature, it is obvious that the manner in which our reference temperatures were measured was far from being precise. However, because of the mechanics of reading the surface temperature from the calibration curve of the infrared scanner system, any error in obtaining the ambient temperature by another measurement technique would only have resulted in approximately the same magnitude of error in the determination of a given surface measurement. Therefore, our calculations are based on the assumption that, although this error is carried through all the equations presented in this report, it is not large enough to warrant a more precise ambient measurement at this time. Once a surface temperature is determined, a complete thermal profile of a surface can be obtained by operating the infrared scanner system in the isothermal mode, as described in Parts I and II (see footnote references, page 1).

The inset on the cover of this report is a photograph of the south- and west-facing walls of Woodbury Hall dormitory on the Dartmouth College campus. The arrows point to the sections of the brick wall (between the first and second floors) where large cast-iron radiators are located on the insides of the rooms. Figure 4 shows one of these radiators.

The cover also shows a thermogram of the same south- and west-facing walls taken on 28 March 1974, at approximately 1930 hours. The ambient air temperature at this hour was -8°C, and the wind was north at approximately 8 miles per hour. The arrows point to two large white zones between the first and second-floor windows on either side of the bay window, which indicate the direct escape of heat from

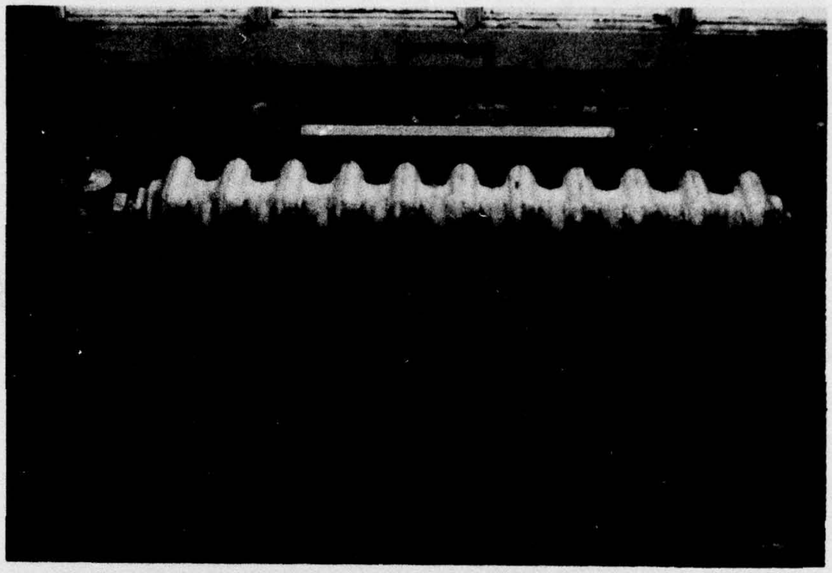

Figure 4. Typical radiator installation at Woodbury Hall. Arrow points to metallic reflector installed behind radiator.

Figure 5a. Thermogram taken on 1 April 1974, after installation of reflectors. Note that the area of heat loss is reduced by about 50% (compare with photograph on cover).

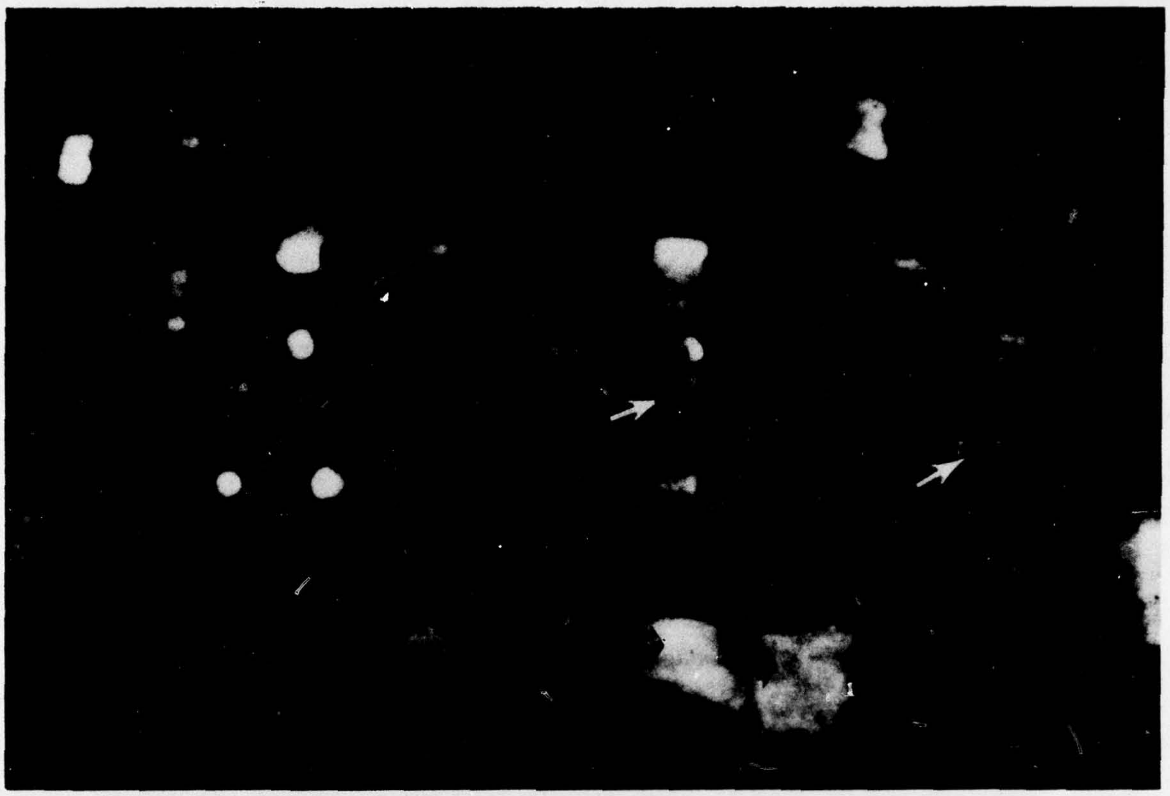

Figure 5b. Thermogram taken on 3 April 1974, after installation of reflectors and insulation of heat riser. Note the difference in area of heat loss compared with that in room below, which had no reflector or pipe insulation.

the two cast-iron radiators located on the wall inside the room in which the bay window is located.

Having been apprised of the escaping heat, Dartmouth personnel suggested that a simple experiment be attempted to determine if sheet metal reflectors placed between the radiators and the wall would retard the flow of heat through the wall. These reflectors were installed by the Dartmouth staff the next day, and we returned on 1 April to take thermograms of the modification. Figure 5a shows a thermogram taken on 1 April 1974, at approximately 2000 hours. The ambient air temperature at this time was 6°C and the wind was north at 4 mph. Again the arrows indicate the location of direct heat transfer through the wall. Notice, however, that the width of the area beneath the window now losing heat has been reduced by about 50%.

The remaining white area was attributed to heat escaping from the heat riser (pipe) located along the radiator and very close to the wall. Again, Dartmouth personnel suggested that we carry the experiment one step further and wrap the heat riser with pipe insulation to see if the remaining heat could be prevented from escaping directly through the wall. They did this and we returned on 3 April 1974 to take additional thermograms of the new modification (Fig. 5b).

The arrows point to the same locations as in the previous two thermograms (Fig. 5a and cover). Note that there are only two relatively small white spots remaining. These are associated with the uninsulated and inaccessible portion of the heat risers between the floor and the ceiling of the room below.

Since it is impossible to repeat the exact setting of the black-white contrast level of the infrared scanner system from one day to the next, the black-white contrast is of necessity different for these thermograms. However, in order to provide a point of reference between Figures 5a and 5b, each thermogram includes the thermal profile of the radiators of the room immediately below the area indicated by the arrows (horizontal black arrows).

There were no reflectors installed behind the radiators in this room; therefore, qualitatively, it can be seen that the extent of heat transfer through the brick wall at these locations was far greater than it was for the room in which reflectors had been installed between the radiators and the wall.

Quantitative results

The standard procedure for calculating heat losses (e.g., of a wall) has been to obtain the overall heat transmission coefficient values of construction materials used in the wall, and then to obtain the temperature difference between the air inside and outside the wall, by using the following equation

$$Q = UA\Delta T \quad (1)$$

where U is the overall heat transmission coefficient (Btu/hr ft^2 °F), A is the area of surface through which the heat flows (ft^2), and ΔT is the overall temperature difference between the inside and outside air (°F). The U value is calculated from experiments that determine the thermal conductivity of individual building materials and their surface conductance to both inside and outside air films.

It is very important to recognize that this method of calculating heat loss is valid *only* where insulation is properly installed and where there are no thermal bridges* or air leaks that can short circuit the heat flow directly from the inside to the outside of the wall without any resistance from the insulation (e.g., 2-in.×4-in. studs in a frame wall or blocking used between studs to support board paneling). Therefore, this method of calculating heat loss always tends to *underestimate* the actual heat loss of a structure.

The method proposed for calculating heat loss with the assistance of an infrared scanner uses the following approach. Since we know that all heat Q reaching the outside wall surface of a structure is lost to the air by radiation and convection,

$$Q = q_c + q_r \quad (2)$$

where q_c is the heat transferred from the wall surface to the air by convection and q_r is the heat transferred from the wall surface to the air by radiation. The net radiation from the wall to the air can be written as

$$q_r = 1.74 \times 10^{-9} Ae (T_w^4 - T_a^4) \quad (3)$$

where T_w is the wall surface temperature and T_a is the air temperature. The surface temperature is obtained from the infrared scanner measurement, the surrounding air temperature is obtained from a thermometer, and the e value is assumed to be either 1 or an approximate value obtained from a handbook.

The convection term q_c is calculated from

$$q_c = U_c A \Delta T \quad (4)$$

where $U_c = f_x$ = the outside surface conductance at wind velocity x (Table I).

It is recognized that there are inherent weaknesses in this approach; viz., in eq 3 the spectral emissivities in the wavelength region 8-14 μ are not known and the air surrounding the wall is treated as a surface at a uniform temperature. However, these considerations must be balanced against the accepted method of heat loss calculation using predetermined U values, since this method is valid only where insulation is installed correctly and where no thermal bridging exists across the insulation. Thermographic inspection has shown, however, that very rarely if ever are there any structures which have the thermal integrity required to allow heat loss to be accurately calculated by the conventional method.

Using eq 2, 3 and 4, the heat loss through the wall area beneath the second floor windows at Woodbury Hall was calculated for the measurements made on 1 April. In order to *project the heat losses* at 22 other dormitories with cast-iron radiators mounted very close to the walls, we adopted the following assumptions:

1. Heat losses from the remaining 22 dormitories and at the radiator locations were identical to those measured at Woodbury Hall.
2. The heat loss measured from the radiator locations at Woodbury Hall was taken as an average annual heat loss.
3. There were 212 heating days in the Hanover area and the heat was on 24 hours/day in all 23 dormitory buildings.
4. All 1100 reflectors reflected the same amount of heat.

** Locations of heat flow from inside to outside of structure without passing through insulation.*

Table I. Outside surface conductance and wind velocity. (Copyright, Industrial Press, Inc.; reprinted by permission.)*

Wind velocity (mph)	*Value of* f_x
0	1.46
5	3.20
7½	4.00
10	4.60
15	6.00
20	7.30
25	8.60
30	10.00

* Strock, C. and R.L. Koral (Co-eds.) (1965) *Handbook of air conditioning, heating and ventilating.* New York: Industrial Press Inc., p. 2-160.

With reference to the discussion in the previous section, the thermograms taken of Woodbury Hall on 1 April (Fig. 5a and 5b) show the thermal profile of a section of the second floor exterior wall as it appeared with a reflector mounted between the radiator and wall and of the first floor immediately below which did not have a reflector inserted between the radiator and the wall. It is recognized that not all experimental parameters were identical in each room (e.g., temperature of both rooms and locations of heat loss). However, it was not possible to completely control the experimental conditions as, to some extent, was desirable because the quantitative results could be directly related to a real life situation.

Based on the assumptions made earlier, the total annual convective and radiative heat losses at all 1100 radiator locations (without reflectors) in the 23 dormitory buildings can be calculated in the following equation:

$$Q_t = (q_r + q_c) \times 24 \times 212 \times 1100 \qquad (5)$$

where 24 = number of hours/day
212 = number of days per heating season
1100 = number of radiator locations fitted with *reflectors*
q_r = radiative heat loss, and is equal to 115 Btu/hr
q_c = convective heat loss, and is equal to 326 Btu/hr
$Q_t = 2.46 \times 10^9$ Btu.

The total annual heat loss at all 1100 locations with reflectors was [using eq 5, with $(q_r + q_c) = 212$ Btu/hr] 1.23×10^9 Btu. These measurements were taken on a day in which there were 28 heating degree-days (hdd). If every day in the Hanover area were exactly the same as this one, it would imply a total of $28 \times 212 = 5936$ hdd in the Hanover area. However, during the past 5 years the average number of heating degree-days has been approximately 8500 per heating season, which is about 1.5 times the number that would occur if all 24-hour periods were exactly the same as the conditions were on 1 April 1974.

The cost of generating 1000 lb of steam at Dartmouth College in 1974 was $4.60. Assuming that each pound of steam produces approximately 1×10^3 Btu, the annual cost of heat loss at the radiator locations without reflectors would be about $16.2 K, and the cost with 1100 reflectors would be about $8.1 K. Based on the preceding assumptions and these costs, *the annual savings would be approximately $8 K at* the 23 dormitories.

This annual savings would have to be tempered by one consideration: the heat is never on in any building constantly 24 hours/day every heating day. Neither is it completely off during any day which has a given number of heating degree-days. Therefore, we can probably assume that the heat is on during the heating season for an average of 12 hours/24-hour period, which would result in a savings of only approximately $4 K. However, the heat loss estimate for the 1100 radiator locations, with and without reflectors, would imply that only 50% of the heat flow was being retarded. If the heat loss could be reduced to 90% by increasing the reflector size and insulating characteristics, the total annual savings would increase to about $7 K.

One important point should be emphasized: the average number of heating degree-days per day in the Hanover area is 8500/212 = 40. The measurements of 28 March were made on a day with 49 hdd, which is much closer to the average value than the figure for 1 April.

Based on the measurements of 28 March, the total annual heat loss at the 1100 radiator locations was estimated to be about 2.3×10^9 Btu, assuming 49 hdd. However, this would imply a total of $49 \times 212 \approx 10{,}388$ hdd, or about 1.2 times more than the average number. By adjusting this value to the average (8500), assuming 12 hours of heat production/24-hour period, and 90% heat loss reduction, we arrive at an estimated annual cost savings of \$8 K. Therefore, a range of potential annual cost savings (\$7 K to \$8 K) can be given for the 23 dormitory buildings.

The monthly energy consumption of each building on the Dartmouth campus is monitored by a condensate meter. Since there were no reflectors in place during the Dartmouth fiscal year July 1973-June 1974, a comparison was made of the energy consumption of the 23 dormitory buildings between that year and the most recent year, July 1975-June 1976, the first complete year after the 1100 reflectors had been installed. That comparison showed that a 3% reduction of energy was achieved, for a total annual savings of approximately \$2.8 K.

Since condensate meters tend to run erratically during periods of both high- and low-flow conditions, the actual usage data may be questionable. In fact, data from two of the buildings had to be discarded because of the abnormally high condensate meter readings for the year July 1975-June 1976. However, since this was the only means of verification, these data were accepted as the actual usage data.

CONCLUSIONS

It is very important to understand that the calculated heating cost savings presented in this report are *potential* savings. In addition, *all* assumptions have to be fully understood before we make these calculations in order to appreciate the difficulty of arriving at quantitative heat loss data for 23 buildings over a complete heating season, from field measurements made on one building over a period of two hours on each of two evenings. These assumptions, and the inability to effect a continuous maximum effort of energy conservation in student dormitory buildings, undoubtedly led to the discrepancy between *calculated* values of heat loss and *realized* values at the 23 dormitory buildings. In addition, the most practical and economical solution to the escaping heat for Dartmouth College resulted in a reflector which was only about 50% of the length of the radiator. If a full-length reflector could have been installed, the cost savings would probably have been about twice the actual savings.

The results obtained in this study, however, have demonstrated that, by using an infrared scanner system, approximate surface temperature measurements can be made; if relevant parameters can be estimated, these can then be transformed into approximate heat loss rates and cost savings. But if more accurate results are required, it will be necessary to generate controlled baseline data using the technique of thermographic inspection. A test measurement program is in progress now at CRREL to provide these data.