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Quantitative Residential Heat Loss Study

Aerial thermograms can be used to assess attic ventilation efficiency provided that there is independent knowledge of attic insulation.

Abstract: *A study of the feasibility of using aerial thermography to quantitatively assess ceiling insulation levels of residential houses was undertaken at the Canada Centre for Remote Sensing (CCRS). Thermal data were acquired with a Daedalus infrared line scanner. The recorded signal was later processed on the image analysis facilities at CCRS. It was found that there was not an unambiguous one-to-one relationship between roof temperature and ceiling insulation values. Roof pitch and attic ventilation have been identified as important factors in the determination of the apparent roof temperature. Both can be partially accounted for in model calculations but reliable quantitative determination of attic insulation levels is still not possible. Aerial thermograms can be used to assess attic ventilation efficiency provided there is independent knowledge of insulation.*

Introduction

Energy conservation is becoming increasingly important as our known sources of easily accessible oil and natural gas decrease. One important aspect of all energy conservation programs is identifying areas where savings may be made. It has been demonstrated that airborne thermal infrared imagery or aerial thermograms collected by an infrared line scanner are useful in locating damaged or poorly insulated flat roofs, operating vents, and damaged heating lines (Lapp, 1977; Tanis *et al.*, 1976; Lawrence, 1976; Clawson, 1978). The usefulness of thermograms for detecting poorly insulated residential homes has not been demonstrated. A ventilated attic space, a sloping roof, and the complexity of the radiation environment all combine to make the interpretation more difficult.

This paper describes the results of our attempt to establish a quantitative empirical relationship between roof temperatures and attic insulation levels using model calculations.

Theory

Detection of heat loss by means of aerial thermography is based upon the supposition that, provided the ambient air temperature is lower than the interior temperature of the house, the roof surface of a poorly insulated house will be warmer than that of a well insulated house, other conditions being equal. Since all surfaces above absolute zero Kelvin emit radiation which depends upon their temperature, at first glance it appears that the determination of the insulating levels in the attic should be straightforward. However, image interpretation is complicated by the following effects:

- the radiation emitted by a surface depends upon its physical properties as well as upon its temperature;
- the energy measured by an infrared line scanner is a combination of emitted and reflected energy; and,
- the heat lost from the interior of a house through the ceiling is dissipated by various mechanisms.

Consider first how the physical properties of a surface affect the amount of radiation which it will emit at a given temperature. All real surfaces emit less radiation than the theoretically best emitter, a blackbody. The extent of the reduction is expressed by the emissivity of the surface which is the ratio of the energy emitted by the surface to

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that which would be emitted by a blackbody at a particular wavelength, λ. All natural surfaces have an emissivity which is less than one and, since reflectivity, $r(\lambda)$, for an opaque object is given by

$$r(\lambda) = 1 - \epsilon(\lambda) \tag{1}$$

all surfaces have reflectivity which is greater than zero. Hence, not only does a surface emit less energy than the theoretically best emitter, it also reflects energy which is emitted by the surroundings. Consequently, the energy received by the infrared line scanner is a mixture of emitted and reflected energy.

This has a substantial impact upon the analysis of thermal imagery of residential houses with sloping roofs. Variations in roof pitch (roof pitch is the tangent of the elevation angle of the sloping part of the roof as measured from a horizontal plane) change the amount of energy received by an infrared line scanner by altering the magnitude of the reflected component of the energy received. This occurs because this reflected component is a combination of radiation emitted by the sky and the surroundings of the house. Since a clear sky appears to be a blackbody at about −60°C while the ground typically appears to be a blackbody near ambient temperature, the ratio of reflected sky to reflected ground energy will vary with changing roof pitch. The apparent roof temperature of the house will change accordingly. The apparent blackbody temperature of a surface is the temperature of a blackbody which is emitting the same amount of energy as the surface within the wavelength interval of observation. To illustrate this change in apparent temperature with roof pitch more clearly, consider the following equation where, neglecting atmosphere which is acceptable over the short atmospheric paths involved, the left hand is the energy received by an infrared line scanner:

$$\int_{\lambda_1}^{\lambda_2} N(\lambda,T_{app})\, d\lambda = \int_{\lambda_1}^{\lambda_2} \epsilon(\lambda)\, N(\lambda,T_r)\, d\lambda + F_r \int_{\lambda_1}^{\lambda_2} \left[1 - \epsilon(\lambda)\right] \epsilon_s(\lambda)\, N(\lambda,T_{sur})\, d\lambda + (1 - F_r) \int_{\lambda_1}^{\lambda_2} \left[1 - \epsilon(\lambda)\right] N(\lambda,T_{sky})\, d\lambda, \tag{2}$$

where

$N(\lambda,T)$ = the energy emitted from a blackbody at wavelength, λ, and temperature, T;
$\epsilon(\lambda)$ = the emissivity of the roof surface;
λ_1 = the lower wavelength limit of sensitivity of the line scanner system;
λ_2 = the upper wavelength limit of sensitivity of the line scanner system;
$\epsilon_s(\lambda)$ = the emissivity of the surroundings to the house;
T_{app} = the apparent temperature of the roof surface;
T_{sur} = the temperature of the surroundings to the house;
T_{sky} = the apparent temperature of the sky;
T_r = the roof temperature;
F_r = the view factor of the roof; and
$1 - \epsilon(\lambda)$ = the reflectivity of the roof surface.

The terms on the right hand side represent, respectively, the energy emitted from the roof surface, the energy emitted from the surroundings to the house which is reflected from the roof towards the infrared line scanner, and the energy which is emitted from the sky which is also reflected to the infrared line scanner.

The view factor for a point on a roof is defined as the percentage of the surface of a hemisphere centered on this point which is subtended by ground objects and hence is a measure of the percentage of the radiation impinging upon the point which is emitted by terrestial surroundings. Figure 1 illustrates the view factor for the one-dimensional case. Its value is the ratio of the arc length AB to AC. Brown (1978) describes the concept of view factor more completely and a method for its calculation.

Finally, there are three main mechanisms for the dissipation of heat which is lost through the ceiling of a house to the attic: (1) radiation from the outer surface of the roof; (2) conduction-convection from the outer surface of the roof; and (3) attic ventilation. Since the infrared line scanner detects only the radiated energy from the surface of the roof, it is important to model these various heat loss mechanisms to determine attic insulation levels. For the analysis of our data a model was developed which considers all three heat loss mechanisms and accounts for different pitch of roofs, attic ventilation rates, and house styles. A detailed description of the model is given by Brown (1978).

DATA ACQUISITION AND ANALYSIS

A residential area in Ottawa with houses of different styles and ages was selected for this study. The CCRS Falcon Fan Jet aircraft was used to collect aerial photographs and thermograms from an altitude of approximately 500 metres above ground level on two separate dates in March and April of 1977 and one in March 1978. The nighttime thermograms were collected at 2200 hours on 31 March 1977, 0100 hours on 11 April 1977, and at 2200 hours on 16 March 1978. The roofs were dry

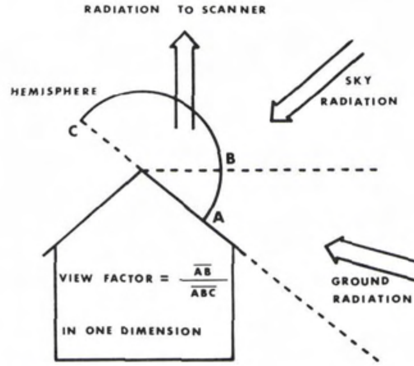

FIG. 1. Residential house roof view factor in one dimension.

and snow-free in all cases. Meterological information is given in Table 1.

The thermal data were collected with a Daedalus infrared line scanner sensitive to radiation in the 8 to 12 μm wavelength region. Two temperature controlled reference plates inside the scanner were adjusted to encompass the range of roof temperatures encountered during the flight, producing a calibrated thermal signal which was recorded by the infrared line scanner, digitized, and stored on computer compatible tapes. These data were then input to both of the image analysis systems at CCRS: the CIAS (CCRS Image Analysis System) (Goodenough, 1979), configured around a PDP-11/70 computer and a General Electric IMAGE-100, and the MICA (Multispectral Image Classification Analyzer), which utilizes a DEC-10 computer and a Bendix MAD or Multispectral Analyzer Display. Using the interactive capabilities of both systems, means and variances for individual roofs were determined and expressed in °C by relating them to the reference plates. Normally, 10 to 30 resolution cells on the roofs were averaged with a resultant standard deviation near 0.3°.

RESULTS

Our initial investigations were to determine whether apparent roof temperature measured directly by an infrared line scanner can be used to qualitatively estimate heat losses through the ceiling of a residential house and, hence, estimate the amount of attic insulation. It was necessary to divide the houses into classes based upon house style because a statistically significant difference (1 percent confidence level) was found between the apparent roof temperature of bungalows, one-and-a-half story houses, and two-story houses. On the 11 April 1977, 0100 hours data set, the average apparent roof temperature of the bungalows was 0.7°C lower than that of the one-and-a-half story houses and 0.5°C lower than that of the two-story houses. The average insulation levels in the attics were essentially the same for the three groups. Insulation levels throughout this paper are expressed as R-value which is a measure of resistance to heat flow, higher values corresponding to greater resistance to heat flow or higher insulation levels. Other studies (OCRS, 1976) have found similar results. These differences in apparent roof temperature are probably due to structural variations, but the exact mechanism causing the difference has not been identified.

Figures 2, 3, and 4 are plots of this apparent roof temperature, measured by the infrared line scanner against the attic insulation R-values, as determined from the questionnaires and on-site visits for 26 bungalows, 38 two-story houses, and 33 one-and-a-half story houses, respectively, for the 11 April 1977, 0100 hours data set. It can be seen that in none of the cases is the slope of the regression line greater than 0.034, which means that there is very little dependence of apparent roof temperature on R-value. The coefficients of determination, which are a measure of the variation explained by the regression line to the total variation, were 0.01, 0.09, and 0.11 for the one-and-a-half story houses, the bungalows, and the two-story houses, respectively. From these only the values for the bungalows and the two-story houses were significantly different from zero at the 3 percent and 5 percent confidence levels, respectively. This means that only about 10 percent of the variations in the apparent roof temperature could be attributed to attic insulation level variations. Hence, by itself, apparent roof temperature is not a reliable estimator of attic insulation levels, and

TABLE 1. METEOROLOGICAL CONDITIONS AT TIME OF AIRBORNE INFRARED DATA ACQUISITION

Date	Time (Local)	Temperature (°C)	Wind Speed (km./hr.)
31 March 1977	2200	1.2°	22–30
11 April 1977	0100	2.0°	10
16 March 1978	2200	−8.0°	9

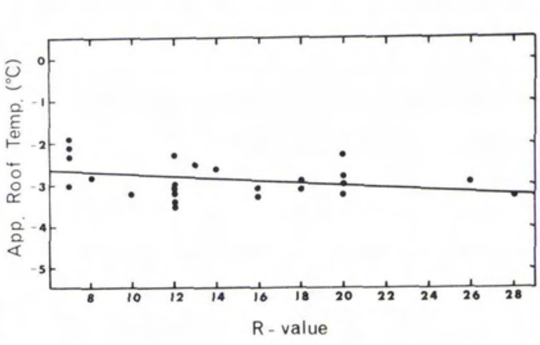

FIG. 2. Variation of apparent roof temperature with attic insulation level for bungalows.

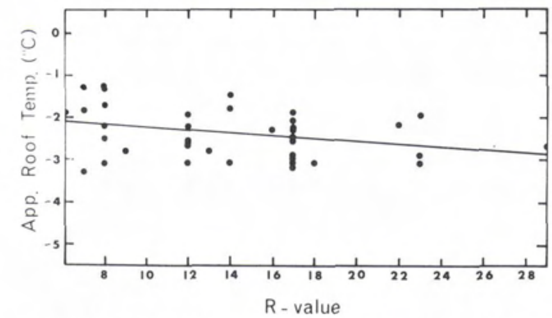

FIG. 3. Variation of apparent roof temperature with attic insulation levels for two-story houses.

other factors must have a significant effect upon the determination of this roof temperature. In this study roof pitch, attic ventilation, and roof emissivity were examined in an attempt to identify the significant factors and to model their effects.

ROOF PITCH

As mentioned previously, houses with different roof pitches reflect different proportions of radiation emitted by the sky and by the house surroundings. The correlation between apparent roof temperature of 26 bungalows on the 11 April 1977, 0100 hour data set and pitch (three classes: low, less than 1/3; medium, between 1/3 and 7/12; and high, greater than 7/12) was calculated and it was found that 10 percent of the variation in temperature could be explained by pitch variations. Using Equation 2, a corrected apparent roof temperature, T_{app}, was calculated assuming that

$$\epsilon_s(\lambda) = 0.9,$$
$$\epsilon(\lambda) = 0.9,$$
$$T_{sur} = \text{ambient temperature, and}$$
$$T_{sky} = 215°\text{K}.$$

The correlation between these corrected temperatures and attic R-value was then calculated for these 26 bungalows. The coefficient of determination increased to 0.17 (3 percent confidence level) from 0.09. This corresponds to a linear correlation coefficient of 0.42. It is therefore evident that roof pitch variations produced differences in apparent roof temperature which have no relationship to variations in attic insulation levels but are caused solely by geometrical changes. Hence, an important first step in analyzing apparent roof temperatures of residential houses is to make a geometrical correction to account for varying roof pitch. We have found that it is possible to reliably separate roof pitch into the three classes from color air photo stereo pairs (scale 1:3000). If this geometrical correction is not made, high pitch roofs will appear substantially warmer than lower pitched roofs. Using Equation 2, a change in apparent roof temperature of 0.6°C was calculated for a roof pitch change from 1/3 to 5/6. This is a significant amount since model calculations (Brown, 1978) have predicted a change in roof temperature of 0.8°C for a change in R-value from R-10 to R-20 for a bungalow with an interior temperature of 20°C, an external air temperature of −10°C, and two attic air exchanges per hour.

ROOF EMISSIVITY

As stated, the energy detected by an infrared line scanner is a combination of emitted and reflected energy. The amount of reflected energy depends upon the roof geometry, sky temperature, and temperature of the surroundings while the amount of energy emitted depends upon the temperature and emissivity of the surface. Any variation in emissivity will appear as apparent temperature variations. In our study variations in emissivity could result from

- different roofing materials,
- the weathering action of sun and precipitation, and
- different color of the roofing material.

All the houses studied had asphalt shingles as the exterior roof layer although the manufacturers may have been different. To determine whether variations in emissivity with age occurred, we looked at the correlation between apparent roof temperature (corrected for roof pitch variations) and house age for the 11 April 1977, 0100 hours data set. The resultant coefficient of determination was not significantly different from zero. The houses were then grouped by color of roof, but again no significant difference was found between the average apparent roof temperatures of the groups.

The possible dependence of emissivity on age was investigated further in the laboratory. Common asphalt shingles of several colors were obtained. Each shingle was cut in two, and one half was stored in a cool, dark place while the other half was exposed to the weathering actions of sun and rain for one year. The emissivities of each pair were then measured in the laboratory by the Defence Research Establishment Ottawa using an

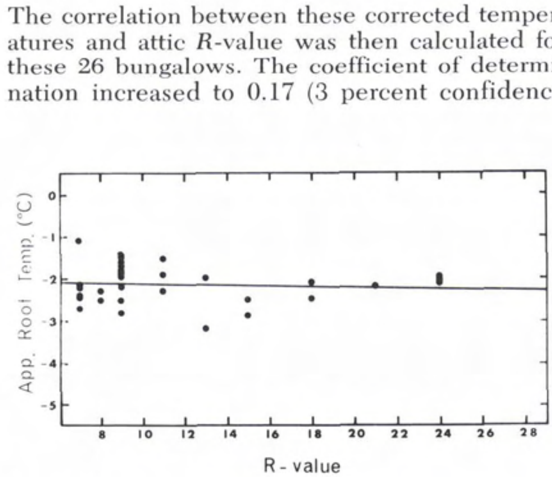

FIG. 4. Variation of apparent roof temperature with attic insulation levels for one-and-a-half story houses.

infrared spectrometer described by Young (1975). No significant change in emissivity between the two parts could be found. Hence, both laboratory measurements and statistical analysis of the 11 April 1977, 0100 hours data set have shown no variation of the emissivity of asphalt shingles with age or color.

ATTIC VENTILATION

Attic ventilation is intended to reduce the surface temperature of the roof by physically removing the warmer attic air and replacing it with air at ambient temperature. Consequently, heat conduction through the roof surface is kept to a minimum, which helps to prevent the build up of ice jams on the roof surface. Unfortunately, this reduces the amount of heat which is dissipated by radiation from the outer roof surface which reduces the thermal contrast between houses with different amounts of attic insulation.

To illustrate the effect of varying attic ventilation rates upon roof temperature, consider the thermal infrared data which were collected on 31 March 1977 at 2200 hours when wind speed exceeded 20 km/hr with gusts to 35 km/hr. The coefficient of determination for the correlation between age and apparent roof temperature, corrected for roof pitch variations, was found to be 0.23, whereas this value for the 11 April 1977, 0100 hours data set when wind speeds were in the range 5 to 10 km/hr. was not significantly different from zero. The factors which could cause a correlation between age and apparent roof temperature are

- changes in emissivity of the roofing material due to weathering,
- different attic insulation levels in houses of different ages, and
- different attic ventilation rates in houses of different ages.

Of these three factors, only the third is a function of wind speed. It has already been shown that changes in emissivity due to weathering are negligible. Also, the average attic insulation levels for the three age classes (less than 5 years old, 5 to 17 years old, and greater than 17 years old) were found to be essentially the same. Hence, it is concluded that the age/roof temperature correlation was due to attic ventilation and that attic ventilation rate is an important parameter in determining apparent roof temperature. Under windy conditions, it becomes the predominant factor while under less windy conditions, it is just one of several factors which contribute significantly to the determination of the apparent roof temperature.

In order to estimate typical attic ventilation rates or the number of air exchanges within the attic per hour, a bungalow with a well ventilated attic space was instrumented with a series of thermistors which measured

- the interior house temperature near the ceiling
- the average attic air temperature,
- the surface temperature of the roof, and
- the ambient air temperature just above the roof.

$$U_c[T_i - T_{at}] = U_r[T_{at}' - T_r] + \text{ventilation loss}, \quad (3)$$

where

U_c = the thermal transmittance of the ceiling of the house,
T_i = the interior house temperature,
T_{at} = the attic temperature at the base of the attic,
U_r = the thermal transmittance of the roof of the house,
T_r = the exterior surface temperature of the roof, and
T_{at}' = the attic air temperature just below the roof and the ventilation loss = $nVC_p[\bar{T}_{at} - T_{am}]$

where

V = the volume of the attic,
C_p = the heat capacity of air at constant pressure,
T_{am} = the ambient air temperature, and
$\bar{T}_{at}$ = the average attic air temperature.

The thermal transmittances, U_c and U_r, are dependent upon the amount of attic insulation and the type of material used to construct the ceiling and the roof. Because this information was known for the test house, these transmittances could be calculated.

Attic ventilation rate, n, was determined from Equation 3 for different wind speeds. The results are shown in Figure 5, which is a plot of ventila-

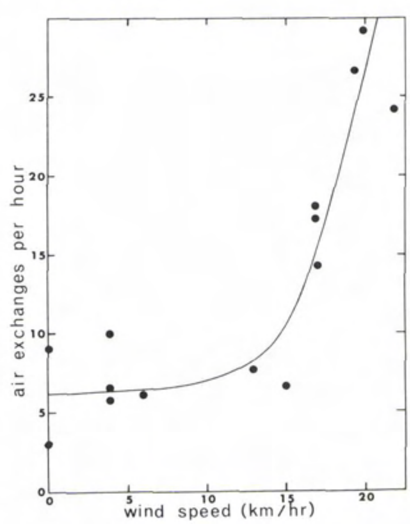

FIG. 5. Variation of attic air exchange rate with wind speed for test house.

tion rate versus wind speed. From this figure it can be seen that the number of air exchanges per hour increases rapidly with wind speed for speeds greater than 10 km/hr. Hence, at wind speeds greater than 10 km/hr, factors related to the efficiency of the attic ventilation rate such as location and type of attic ventilation openings and vents, wind direction, and local topography become important.

It was found that attic ventilation rates could be qualitatively estimated from an examination of aerial photographs (Brown *et al.*, 1978). This estimation was based upon a knowledge of house style and age, and an examination of the photographs for roof vents. When this attic ventilation information was incorporated into model calculations of attic insulation levels and corrections for roof pitch were made, the coefficient of determination relating the actual R-value (as determined from the questionnaires and on-site visits) and the R-value as determined from the model calculations was found to increase from 0.09 to 0.41. Attic ventilation appears to be a major contributing factor to the determination of the apparent roof temperature. Although attic ventilation can be qualitatively assessed from the air photographs, the effects of local topography on wind patterns around the houses and vents operating in a sub-optimal manner are almost impossible to predict. Hence, model calculations still cannot accurately determine attic insulation levels even when attic ventilation is modeled. In addition, assessing theoretical attic ventilation rate is a very labor intensive operation and impractical under operational conditions.

For a technique to be reliable, it is important that there be a consistency in the measured parameter from one data set to the next. To investigate whether this consistency was present in the thermograms of residential houses, data collected on 16 March 1978, 2200 hours was compared with those collected on April 11 1977, 0100 hours. A parameter, p, was introduced and defined as

$$P_i = \frac{T_i - \bar{T}}{\sigma} \tag{4}$$

where

T_i = the average roof temperature of the ith house,

$\bar{T}$ = the average apparent roof temperature of all the houses used in the analysis, and

σ = the standard deviation of the T_i about $\bar{T}$.

The coefficient of determination between the P_i was calculated to be 0.74 (coefficient of correlation = 0.86). In contrast, the corresponding coefficients of determination between the P_i for the 31 March 1977, 2200 hours data and the 11 April 1977, 0100 hours data and the 16 March 1978, 2200 hours data were 0.23 and 0.30, respectively. This would be expected because of the effect of wind discussed above.

Thus, it appears that the aerial thermograms produce consistent apparent roof temperatures from data set to data set and the results from the analysis of one data set can be trusted if care is taken to collect the thermograms under low wind, clear sky conditions.

After examining various approaches, we have concluded that it is very difficult or perhaps impossible to reliably estimate attic insulation levels from an examination of aerial thermograms because of other factors, particularly attic ventilation. Aerial thermograms, however, may possibly be used to assess attic ventilation efficiency if attic insulation levels are known. This in itself is valuable because attic ventilation efficiency is something which cannot be easily assessed by a homeowner.

Presently, in most energy conservation programs, the aerial thermograms of residential houses are normally analyzed with the aid of the house owner. If the owner informs the interpreter that his house has R-30 insulation levels in the attic and the house still appears very warm after corrections for roof pitch, there is likely a problem with the ventilation, improperly installed insulation, or air leakage into the attic from the interior of the house. If attic ventilation is the cause, this can lead to a build-up of moisture in the attic, deterioration of the insulation, and in extreme cases to structural damage. Poor attic ventilation will result in more heat being lost by conduction through the roof surface. This escaping heat may melt snow, which can run down the roof surface only to freeze near the cold eaves.

The subsequent ice jams and build-up of ice and water under the shingles can result in roof damage. It is therefore important to know when attic ventilation is inadequate, and this information can effectively be provided by aerial thermograms.

Conclusions

Apparent roof temperature of residential houses with a sloping roof and ventilated attic space is not a reliable or accurate indicator of attic insulation levels. Attic ventilation and roof pitch play major roles in the determination of roof apparent temperature. Corrections for roof pitch variations can be easily made based purely upon geometrical considerations, provided some means of assessing roof pitch (such as stereo photographs) is available. Expected attic ventilation rates can be qualitatively determined from daytime photographs, provided the interpreter has a good knowledge of construction practices in the area. Changes in the emissivity of asphalt shingle roofing material have been found to be negligible.

Attic ventilation appears to be a strong factor affecting the determination of roof temperature. Although ventilation rates can be qualitatively assessed, model calculations are unable to account for this effect adequately because local topography modifies wind circulation around a structure and because of unseen effects such as vents operating below peak efficiency.

Experience from public awareness programs and our analysis suggests that aerial thermograms provide a good means of assessing attic ventilation efficiency provided the interpreter has independent knowledge of attic insulation levels. In an energy conservation program which uses aerial thermography, this information could be supplied by a home owner who can determine the attic insulation far more easily than attic ventilation efficiency.

References

Brown, R. J., 1978. Infrared Scanner Technology Applied to Heat Loss Determination, *Canadian Journal of Remote Sensing*, 4, pp. 1-9.

Brown, R. J., P. M. Teillet, and J. Cihlar, 1978. The Effects of Attic Ventilation on Residential Heat Loss Analysis, *Proceedings of the Fifth Canadian Symposium on Remote Sensing*, Victoria, B.C., pp. 219-225.

Clawson, R., 1978. Infrared Thermography on a Physical Plant Setting, *Proceedings of Thermosense I*, Chattanooga, Tennessee.

Goodenough, D. G., 1979. The Image Analysis System (CIAS) at the Canada Centre for Remote Sensing, *Canadian Journal of Remote Sensing*, 5, pp. 3-17.

Lawrence, G. R., 1976. Airborne Thermal Sensing Programs for the Detection of Heat Loss, *Proceedings of the Canadian Symposium on Thermography and Energy Conservation*, Toronto, Ontario and Montreal, Quebec.

Ontario Centre for Remote Sensing (OCRS), Ministry of Natural Resources, 1976. *Detection of Heat Loss from Buildings by Remote Sensing: Summary of Technology*, report prepared for the Ministry of Energy.

P.A. Lapp Ltd., 1977. *The Assessment of Heat Loss from Buildings by Means of Aerial Thermography*, report to the Canada Centre for Remote Sensing.

Tanis, F. J., R. E. Sampson, and T. W. Wagner, 1976. *Thermal Imagery for Evaluation of Construction and Insulation Conditions of Small Buildings*, Environmental Research Institute of Michigan, Report No. 116600-12-F.

Young, B. G., and R. J. Brown, 1975. *A Procedure for Measuring Thermal Emission Spectra at Ambient Temperature*, Defence Research Establishment Report No. 708, 50 pages.

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