Aerial Measurement of Heat Loss

Phase 1

July 1979

MASTER

**DOE/CS/20415-T1
NYSERDA 79-10**

U.S. Department of Energy

**Assistant Secretary for Conservation & Energy
Office of Buildings & Community Systems**

**New York State Energy
Research and Development
Authority**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

AERIAL MEASUREMENT OF HEAT LOSS

PHASE I

DOE/CS/20415-T1
NYSERDA 79-10

July 1979

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Prepared for

UNITED STATES DEPARTMENT OF ENERGY
Assistant Secretary for Conservation and Energy
Office of Buildings and Community Systems

Project Manager
John Cuttica

NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

Project Manager
Joseph Rizzuto

Prepared by

CALSPAN CORPORATION
Buffalo, New York

Project Manager
John R. Schott

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

This report was prepared as an account of work sponsored by the United States Government and the State of New York. Neither the United States nor the State of New York nor the United States Department of Energy, the New York State Energy Research and Development Authority, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, the State of New York, or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government, the State of New York, or any agency thereof.

FRONTISPIECE

This daytime color photo and nighttime thermogram of part of Syracuse University represent the type of imagery analyzed on this program. These images contain a great deal of information about the construction of the buildings, the temperature of the buildings and about the heat being lost from the buildings. Much of this information is not extractable from the images simply by viewing them. This report discusses research directed at development of techniques to extract meaningful objective information from aerial thermograms. Because the information obtained simply by viewing a thermogram is limited and can be misleading, this is the only image included in this report. We would hope that the reader would initially look at the thermogram with the common perception that the brighter the image - the hotter the object and hence the greater the heat loss. After reviewing this report we would suggest you view the image again, hopefully with a somewhat modified perspective.*

* A quantitative analysis of these images is contained on pages 86 and 87.

TABLE OF CONTENTS

<u>Section</u>	<u>Title</u>	<u>Page Number</u>
	LIST OF ILLUSTRATIONS.....	iv
	LIST OF TABLES.....	v
	ACKNOWLEDGEMENTS.....	vi
	EXECUTIVE SUMMARY.....	vii
1	INTRODUCTION AND SUMMARY.....	1
2	DEFINITION OF THE PROBLEM.....	3
	2.A Radiation Theory.....	4
	2.B Infrared Scanners.....	8
	2.B.1 Signal Processing in the Infrared Scanner.....	8
	2.B.2 Thermogram Geometry.....	8
	2.C Literature Review.....	9
3	ATMOSPHERIC AND BACKGROUND EFFECTS.....	16
	3.A Theoretical Approach.....	16
	3.B Calibration Procedures: Profile Technique.....	21
	3.C Evaluation of the Profile Technique.....	26
4	EMISSIVITY.....	33
	4.A Emissivity Measurements.....	33
	4.B Calspan Approach.....	35
	4.B.1 Theoretical Procedures for Measurement of Emissivity.....	35
	4.B.2 Instrument Design and Operation.....	36
	4.B.3 Emissivity Results.....	38
5	MATERIAL IDENTIFICATION.....	41
	5.A Photometric Technique.....	41
	5.A.1 Photographic Effects.....	41
	5.A.2 Atmospheric Effects (Photographic).....	42

<u>Section</u>	<u>Title</u>	<u>Page Number</u>
	5.A.3 Classification Approach: Multi-variate Statistics.....	48
	5.A.4 Photometric Results.....	48
	5.B Biband Ratio Technique.....	53
	5.B.1 Biband Ratio Approach.....	53
	5.B.2 Biband Results.....	56
	5.C Photometric and Biband Results.....	56
6	AERIAL MEASUREMENT OF TEMPERATURE.....	58
	6.A Procedures.....	58
	6.B Error Analysis.....	68
	6.C Results of the Error Analysis.....	71
7	HEAT LOSS MEASUREMENTS.....	76
	7.A Relationship Between Heat Loss and Temperature.....	76
	7.B Approach to Heat Loss Measurement.....	79
	7.C Heat Loss Error Analysis.....	81
8	CONCLUSIONS AND RECOMMENDATIONS.....	85
9	REFERENCES.....	89
	APPENDICES	
	A. Geometric Scenario for Estimating Skydome and Background Fractions.....	A-1
	B. Data Collection Procedures.....	B-1
	C. Computer Programs for Data Analysis and Theoretical Modeling.....	C-1
	D. Signal Processing in Infrared Scanners	D-1
	E. Statement of Work.....	E-1

LIST OF ILLUSTRATIONS

<u>Figure No.</u>		<u>Page Number</u>
2.A-1	Atmospheric Transmission of the Electromagnetic Spectrum and the Blackbody Radiation Curve for a 300°K Object.....	7
3.A-1	Energy Paths Described by Equation 3.A-3.....	19
3.B-1	Thermal Images Obtained During a Profile.....	24
3.B-2	Illustration of How the Profile Data are Collected.....	25
3.B-3	Plot of Temperature vs. Altitude Illustrating Atmospheric Variation in Observed Temperature for Four Profiles.....	26
3.B-4	Example of Parallel Flight Lines Over a Power Station Showing the Change in Look Angle for a Given Ground Point.....	27
3.B-5	Example of Energy Equations for a Given Point for a Change in Look Angle.....	28
3.C-1	Comparison of Surface and Aerial Temperature Measurements..	31
4.B-1	Schematic Diagram for the Emissometer (Cross-Section).....	37
5.A-1	Atmospheric and Illumination Effects Involved in Establishing the Exposure of a Body of Water.....	43
5.A-2	Typical Calibration Curves for a Color Image at a Scale of 1:40,000.....	45
5.A-3	The Experimental Photointerpretation Console.....	47
5.B-1	Results of the Biband Ratioing Material Identification Algorithm.....	55
6.A-1	Energy Paths in the 8-14 μ m Bandpass According to Equation 6.A-2.....	59
6.A-2	Illustration Showing Calculation of the Fractional Parts of the Skydome which Represent Sky (F) and Background (1-F).....	61
6.A-3	Flow Chart for Temperature Measurement Using Comprehensive Analysis Including Thermograms, Color Photographs and Owner Interaction.....	62
6.A-4	Flow Chart for Temperature Measurement Using Only Owner Interaction and Thermal Imagery.....	65
6.A-5	Flow Chart for Temperature Measurement Using Only Photographic and Thermal Imagery.....	66
7.A-1	Energy Exchange at a Roof Surface According to Equation 7.A-2.....	78

LIST OF TABLES

<u>Table No.</u>		<u>Page Number</u>
3.C-1	Comparison of Surface and Aerial Data for 24 September 1976.....	29
3.C-2	Comparison of Surface and Aerial Data for 9 July 1976.....	29
4.B-1	Emissivity Values for Common Roofing Materials.....	37
5.A-1	Multivariate Classification Accuracies: Photometric Technique Using Reflectances and Ratios Combined.....	50
5.A-2	Material Classes for the Training Set Data.....	51
5.A-3	Results of Classification of Material Types Into Emissivity Groups.....	52
6.B-1	Error Analysis for Calibration of Actual Water Temperatures.....	70
6.C-1	Three Examples of Error Analysis Showing the Effect of Different Types of Precision	72
6.C-2	Example of Two Roofs with Identical Apparent Temperatures on a Thermogram but with Markedly Different Actual Temperatures.....	74
7.C-1.a	Results of Applying the Heat Loss Model in the Case of a Fixed Apparent Temperature.....	83
7.C-1.b	Results of Applying the Heat Loss Model in the Case of a Fixed Apparent Temperature.....	84

ACKNOWLEDGEMENTS

We extend our thanks to Dr. Fred Strnisa and Joseph Rizzuto of NYSERDA and Dr. George Courville and Mr. John Cuttica of USDOE for their support of this effort and their many valuable discussions. Many individuals at Calspan contributed to the success of this effort and preparation of this report. Particular thanks go to Liz Wilkinson for preparing the literature review; Cindy Kirby for invaluable technical support and for preparation of Appendices A and C and to Tim Gallagher for his cooperation in the development of the emissometer. We would also like to express our thanks to Herb Kaufman, formerly of NYSERDA, who helped get this program off the ground and to the members of the Steering Committee for their input throughout the program.

EXECUTIVE SUMMARY

The overall objective of the program reported here was to evaluate the feasibility of aerial measurement of rooftop heat loss. Any attempt at calculation of rooftop heat loss involves roof surface temperatures as an input. Therefore, identification of a precise technique for aerial measurement of rooftop temperature values became a major goal of this research. The major obstacle encountered in evaluating procedures for aerial measurement of temperature was development of a technique for incorporating material emissivities in the calculation. Resolving the problems associated with emissivity effects on temperature calculation became one of the major tasks for this program. (cf. Appendix E, The Statement of Work).

The approach identified for aerial measurement of heat loss proceeds as follows: (1) Collect nighttime aerial thermograms and, depending on analytical approach, collect daytime color photography; (2) calibrate the aerial thermograms to permit correction for atmospheric attenuation, flare light and sky background effects; (3) using classical or quantitative-photometric interpretation of color photographs or through owner interaction, identify the roofing material(s) on a given structure; (4) use look-up tables to associate an emissivity with the roofing material; (5) use emissivity values, and atmospheric calibration data, to correct energy levels (brightness value) recorded on the thermogram to actual rooftop temperature values; (6) use heat exchange models to calculate heat loss utilizing roof temperature as a major input variable to heat loss models.

The state-of-the-art of aerial thermogram interpretation is based on the practice of directly associating an apparent temperature with each energy level on a thermogram. However, this approach neglects the fact that the atmosphere affects the contrast on a thermogram causing the apparent temperature, as well as apparent temperature differences, to change. Also neglected in this approach is the fact that variations in the emissivity of roofing materials affect apparent temperature values to a point where a warm object can appear cooler than an object whose actual temperature is several degrees less than the

warmer surface. The approach defined as part of this effort takes into consideration the problems associated with this method. The improved approach results in a more precise interpretation of roof temperature, allows for comparison of changes over time, and greatly reduces the possibility of misinterpretation.

The elements of the approach developed here combine to permit precise measurement of roof-top temperatures. Each element also deserves consideration on its own merits as a means of improving qualitative interpretation of aerial thermograms. The atmospheric calibration techniques are valuable because knowledge of atmospheric parameters will permit interpreters to better evaluate temperature differences associated with brightness fluctuations. Atmospheric transmission, for example, can typically range between 0.85 and 0.95 for different data collection conditions. Under different atmospheric conditions, the same amount of fluctuation in brightness would be correctly interpreted as a different temperature change provided atmospheric effects have been accounted for.

Several alternate procedures were determined for identification of roofing materials. The photometric technique involves densitometric analysis of daytime color aerial photography. This allows discrimination of a number of different roofing types and subtypes. In addition, it offers the potential for automation of material type, permitting the generation of temperature maps prior to homeowner involvement. Emissivity measurements, indicating that detailed material discrimination might not be necessary, suggested the possibility of classical photointerpretation combined with owner interaction as a means of material identification. Although this has the advantage of reduced cost, the final analysis for temperature would have to be done while the owner was viewing the thermogram. A third approach to thermogram material identification simply involves the owner knowing the roofing material. While this conceptually describes the simplest approach, experience indicates that some effort must be made to educate homeowners to help them in correctly identifying roofing materials.

Obviously, the need to know roofing material type is only important if we want to account for emissivity effects. A major part of this effort was directed at establishing the emissivity values of roofing materials. Over 30 different materials were studied establishing a library of emissivity values

appropriate for use with aerial thermograms. In certain cases, different types and ages (i.e., weathered vs. new) of material within a basic group were studied. For example, several different colors, weights and ages of asphalt shingles were studied. The results of these studies, although presently based on limited data, indicate that variation between material groups can be substantial; however, there does not appear to be significant variation within a group. For example, of the 14 asphalt shingles studied, the standard deviation was only 0.018, about a mean value of 0.91. In addition, the most common roofing materials do not appear to have significant variation with look angle. (Smooth surfaces such as galvanized metal, slate and glass do show significant variation in emissivity with look angle; however, more detailed study will be required to quantify these effects). This set of emissivity data is valuable not only in quantitative analysis, but also in the qualitative interpretation of thermograms. If the roofing material is determined through any of the methods suggested above, then interpreters can, in a qualitative fashion, factor emissivity into their analyses. Consequently, they will not immediately assume a cool-appearing house has a low temperature if they know it has a low emissivity.

In an attempt to define the potential utility of quantitative thermographic analysis, limited error analyses were undertaken. We can consider potential errors at many different stages in the analysis including where we are with current techniques, where we can be (using the technology identified here), and where we can expect to go. Using a "brightness equals temperature" approach, we can anticipate errors of several degrees centigrade in comparing roof elements. Generally, this means that only variations in individual roof elements composed of a single material should be made. Comparison of nearly-identical roofs in terms of construction style and material can be made but with limited confidence. Use of the tools developed during this effort should, in a qualitative fashion, enable greater confidence in interpretation and inter-comparison of more structures. However, the limits of such a subjective approach are difficult to evaluate. Quantitative application of the approach suggested here should lead to temperature measurement capabilities to within about 1°C of actual values. This will permit more confident, objective evaluation of temperature differences occurring within complex structures, between structures, and over time in the same structure.

In the future, greater precision in temperature measurement should be expected to follow from on-going improvements in the technology. Once accurate temperature mapping is available, heat flow analysis can be performed and a direct assessment of heat loss from rooftops will be possible. This represents a significant improvement over present technology which utilizes apparent temperature values to estimate heat loss. While apparent temperature, actual temperature and heat flow are related, the relationship is by no means a simple linear function. Obtaining an objective approach to heat flow (which is the real element of concern for energy conservation) will be a major technical advance. At present, it appears that a meaningful assessment of heat flow will be possible if measurement accuracies within 0.5 to 1°C of actual values can be achieved.

In concluding, we should point out that many of the measurement values and theoretical approaches presented in this report are also applicable to ground-based efforts.

SECTION 1

INTRODUCTION AND SUMMARY

Aerial thermography is being used on a large scale to promote energy conservation ostensibly by pointing out structures or parts of structures having high heat loss. The concept is quite simple and extremely attractive from a public relations and economic perspective. The physical concept stems from the fact that aerial infrared systems image the radiant energy emitted from entire communities as they are overflown. The radiant energy emitted from any object not at absolute zero varies as a function of temperature. In turn, the temperature of a structure should vary as a function of how much heat is lost through the roof. We therefore expect energy levels, recorded on the thermograms as shades of grey, to vary as a function of the heat lost through the roof element imaged. Nearly all thermography interpreted today for heat loss is based completely on this conceptual logic (i.e., that the brighter the image, the warmer the surface and the greater the heat loss). Conceptually, there is nothing fundamentally wrong with this logic. In practice it neglects several fundamental problems. The heat lost through a roof surface is a function of roof temperature, but it is also a function of several other variables. As a result, a roof which is cooler than another may actually be losing more heat. In the same way, roof temperature is a factor in how much energy is radiated by the roof but it is not the only factor. Indeed, the energy imaged as a roof element on a thermogram comes from at least three sources, only one of which is the roof itself, and temperature is only one of several factors affecting the roof term. It is possible to have substantial temperature variations go undetected or even be misinterpreted as to the direction of change because of these effects.

The research reported here involved efforts to eliminate some of the limits of classical subjective interpretation of thermograms. In particular, the work reported here was directed at determining if a technique could be defined to allow measurement of roof temperature from thermograms. The philosophy being that if a technique for measurement of temperature could be defined, then it would be reasonable to initiate efforts to define a technique to

objectively assess heat loss using thermography. In essence then, this effort was directed at the first of two major steps separating us from being able to authoritatively address the heat loss problem. In addition, the results of this study provide a better basis for assessing the capabilities and limitations of the qualitative use of aerial imagery in heat loss determination.

As a result of the work reported here, we believe the major part of that first step has been successfully completed. A technique for measurement of rooftop temperature using aerial thermograms has been defined and is ready for testing. The technique involves flight procedures that permit empirical measurement of the major atmospheric and background parameters affecting the recorded energy. It also involves measurement of background radiation directly from the thermograms. How well a roof surface radiates (i.e., its emissivity) is determined from laboratory data generated as part of this effort and from knowledge of material type. Several procedures for determination of material type are presented as part of this report.

The measurement technique identified in this report is expected to allow determination of roof temperature values perhaps to within 1°C of their actual value. With this type of measurement, it becomes more reasonable to consider objective evaluation of rooftop heat loss. Some initial directions for studies of heat loss are suggested in Section 7 of this report. Section 8 includes recommendations for testing of the procedures for temperature measurement which we feel should be carried out simultaneously with attempts to define techniques to complete the effort started here for objective measurement of heat loss.

SECTION 2

DEFINITION OF THE PROBLEM

The current state-of-the-art of heat loss measurement using infrared thermography leaves much to be desired. There are several reasons for this. Among them are oversell by promoters, misinterpretation of capabilities by users; limitations of collection and analysis techniques, and the fact that the final interpretation is often performed by a completely untrained observer unaware of any of these limitations. The goal of aerial thermography is to provide a means whereby an individual can objectively evaluate the thermal integrity of his property. Is an excessive amount of heat being lost through the shell of the structure? To date the few efforts that have attempted to objectively answer this question using aerial thermography applied to residential structures have been unsuccessful. The results of attempts to objectively evaluate commercial structures have been mixed.

To objectify the determination of heat loss several factors must be considered. We must recognize that heat can be lost by conduction, convection, and radiation. In addition, factors such as attic ventilation, roofing material, windspeed, roof pitch, proximity to other objects, air temperature, and sky irradiance, as well as insulation, govern the loss of heat from a structure. When attempting to determine the heat lost from a structure, the roof surface temperature, under approximately steady-state conditions, becomes a very important, but by no means, definitive parameter (i.e., it is necessary but not sufficient for determination of heat loss). This is where thermography comes into play.

Thermograms contain information related to the radiant energy reaching an airborne sensor from objects on the ground. The energy radiated from an object on the ground is a function of its temperature. Hence, it is assumed a thermogram can provide a means for remote measurement of roof temperature which, as we have indicated, is an important parameter in objectifying building heat loss. A problem arises, however, when we more closely examine the factors concerning what a thermogram really sees. This problem results because the energy reaching the sensor that forms the thermogram is not only a function of the temperature of the roof, but is also significantly affected by the roofing

material (emissivity), adjacent buildings (background radiation), and sky conditions (atmospheric transmission and air radiance). Thus, to use thermography as a key to objective evaluation of heat loss, the factors that go into forming the thermogram image must be properly accounted for.

The program discussed in this report has been directed at developing procedures to permit aerial measurement of rooftop temperature. We perceive this to be the critical step in objectifying the determination of heat loss from buildings. Once again, we must stress that it is not sufficient to know temperature, but as we outline in Section 7, methods for evaluating most of the other factors governing the determination of heat loss have been suggested.

2.A Radiation Theory

Aerial thermal scanners generally detect radiation in the 8-14 μ m bandpass. This section will discuss how the radiant energy detected by a sensor at aircraft altitudes (~ 600 m) is a function of temperature. The energy observed is also functionally dependent on atmospheric and background terms and will be discussed in Section 3. This section is intended as a general introduction to the fundamental concepts of radiation theory pertinent to aerial measurement of temperature. More detailed discussions can be found in Wolfe et al. 1965, Holter et al. 1962 and Hudson 1969.

All matter at temperatures above absolute zero radiates electromagnetic energy. The relation between radiant energy, W (emittance), and temperature, T, in $^{\circ}$ K, is expressed by the Stefan-Boltzmann equation

$$W = \sigma T^4 \quad (2.A-1)$$

where σ is a proportionality constant.

The general equation for a blackbody radiator is given by the Planck distribution equation

$$W_{\lambda} = 2\pi c^2 \lambda^{-5} (e^{hc/kT} - 1)^{-1} \quad (2.A-2)$$

where W_λ is the radiant emittance per unit wavelength interval,
 c is the speed of light,
 h is Planck's constant,
 k is Boltzmann's constant
 T is temperature, and
 λ is wavelength

This equation, derived from quantum physics, is a function of the quantum radiation states within a blackbody cavity.

The Stefan-Boltzmann equation is obtained by integrating the Planck equation over all wavelengths.

The problem in using these equations is finding the dependence of W on temperature over a defined bandpass. The Stefan-Boltzmann equation indicates that radiant emittance integrated over all wavelengths varies as T^4 , i.e.,

$$\int_0^\infty W_\lambda d\lambda = W = \sigma T^4 \quad (2.A-3)$$

To find the functional dependence on temperature in a finite bandpass, it is necessary to use a series expansion solution to the normalized integral of radiant emittance. This yields the fraction of energy less than a given wavelength, λ , given by

$$D = \frac{\int_0^\lambda W_\lambda d\lambda}{\int_0^\infty W_\lambda d\lambda} \quad (2.A-4)$$

The D values are tabulated (cf. Pivovonsky and Nagel 1961) in standard blackbody tables for ranges of T , λ or λT combinations. By finding the difference in D for two wavelengths, a relation can be developed between temperature and radiant emittance in a bandpass expressed as a fraction of the total radiant emittance.

If D is the fraction of the total energy emitted by a blackbody between the wavelength 0 and λ , then $D_2 - D_1$ is the fraction of emitted energy between λ_1 and λ_2 . Since σT^4 is the total energy for a given temperature, then

$W = (D_1 - D_2) \sigma T^4$ is the radiant energy emitted for a given bandpass. Values of W and T over the range of interest can be stored in data files on a computer. T can then be calculated from the stored W values.

We can therefore express the radiant energy from a blackbody over the 8-14 μ m bandpass ($W_{\Delta\lambda}$) as

$$W_{\Delta\lambda} = W_T = \int_8^{14} 2\pi c^2 \lambda^{-5} (e^{hc/kT} - 1)^{-1} d\lambda \quad (2.A-5)$$

This expression, however, is only true for a blackbody. A blackbody is a perfect radiator and absorber; therefore, all the incident energy is absorbed and reradiated. In practice, the bodies we will be concerned with will be gray bodies whose emissivity is constant over all wavelengths or with bodies whose emissivity varies with wavelength. In either case, they are not perfect absorbers or radiators in the 8-14 μ m bandpass and thus, have emissivities less than unity.

Emissivity (ϵ) is the ratio of the energy radiated from a source to the energy radiated from a blackbody at the same temperature. Thus, for a gray body

$$W = \epsilon W_T \quad (2.A-6)$$

There are several reasons for using the 8-14 μ m spectral bandpass for aerial infrared measurements. The principal ones can be seen in Figure 2.A-1. This figure shows atmospheric transmission as a function of wavelength together with the blackbody radiation curve for a temperature of about 300°K (approximately earth ambient). To optimize the relatively low signals radiated from objects at approximately ambient temperatures, we want to work near the peak in the radiation curve and at wavelengths where the atmosphere is transparent (i.e., an atmospheric window). The 8-14 μ m window satisfies these requirements.

FIGURE 2.A-1 Atmospheric Transmission of the Electromagnetic Spectrum and the Blackbody Radiation Curve for a 300°K Object

2.B Infrared Scanners

The radiant energy from the ground is processed by airborne infrared scanners into aerial thermograms. Several steps are involved in this process which enables us to relate the energy received to equivalent blackbody temperature values. This section will outline the signal processing through an infrared scanner as well as thermogram geometry.

2.B.1 Signal Processing in the Infrared Scanner

A thermal scanner collects the radiant energy from objects on the ground and displays the relative energy levels observed as gray tones on a thermogram. In order to relate gray tones to energy levels and/or apparent temperature values, the data must be carefully processed. The effects of film processing, film transport speed, and the electronic signal processing must be accounted for to account for all these effects. Voltage-controlled step wedges must be placed on the film and the blackbody and gain control setting must be carefully calibrated. The details of this process are included in Appendix D.

2.B.2 Thermogram Geometry

Because thermograms are not photographs, they often have considerable geometric distortion which may sometime affect image interpretation. The geometric distortions common to scanner systems are referred to as roll, tangent and v/H error. The roll error is due to changes in the area imaged by the scanner associated with aircraft roll. It is compensated for either by mechanical stabilization of the scanner or by electronic delay in the imaging signal proportional to aircraft roll. The tangent error and v/H error result respectively from the imaging process and errors in setting the film transport speed. They can be corrected by appropriately stretching the image when it is redisplayed on a CRT display in the laboratory. Appendix D contains a more detailed discussion of thermogram geometry.

* v = Aircraft speed
 H = Altitude above the ground

2.C Literature Review

Since the early 1950's, advanced study and increasing interest in the principles of infrared (IR) radiation have stimulated the development of the technology now known as thermography. Scientists and engineers, intrigued with the apparent versatility of the technology, began to utilize it in a number of environmental, health science, and energy applications. With the development and refinement of techniques to measure IR radiation, methods to record the information in the form of thermograms were first completed in 1956 in the health science field. After that time, progress accelerated in all fields and soon thermography was being utilized in both ground-level and aerial measurements of infrared radiation from various surfaces. Early environmental applications included studies of soil moisture, geology, vegetation, water bodies, geothermal activity and thermal pollution from industrial discharges. In the early 1970's, the use of thermography in energy applications began with the study of thermal energy (heat) losses from building sidewalls, windows and rooftops. These studies were aimed primarily at the evaluation of insulation integrity.

Development of improved instrumentation for measuring apparent surface temperatures and the increasing desire to establish improved energy conservation practices, stimulated the growth and popularity of using thermographic techniques to evaluate heat losses from large areas of residential and business communities. These area-wide surveys, employing both aerial and ground-level thermal scanning techniques are economically and scientifically attractive because of the rapid and relatively inexpensive methods by which thermal data can be collected and analyzed. However, the extensive use of thermography, particularly in the survey work, has caused many questions to surface regarding the use and interpretation of the data contained in the thermograms. The remainder of this section will present, by means of a literature review, the development of the current technology and some of the most recent evaluations of the state-of-the-art of thermography as applied to heat loss studies.

In 1972, Paljak and Petterson published the first comprehensive manual describing standard theory and techniques employed in using an infrared camera system (in the 2-5.6 μ m band) to determine insulation defects in buildings.

Although the authors discuss the principles of determination of absolute temperature distribution from information derived from the IR scanning system, they later state that, "The use of the measurement of surface temperature (thermography) must be confined to the location of defects in thermal insulation and possibly to the determination of the type of defect." This work is still frequently referenced today but usually for information on the many thermograms of building material defects contained in the manual.

Ground survey systems, such as those described in the Paljak and Petterson manual, are still widely used for heat loss studies from windows, building sidewalls and industrial apparatus (boilers, blast furnaces, steam lines, etc.) A variety of these thermal scanners and data recording systems is available, most of which detect radiation emitted in the 2-5.6 μ m wavelength band. The use of these systems to measure apparent surface temperature is a wide-spread application of the current technology and is used for qualitatively determining heat loss from building surfaces. Aerial surveys of large residential areas and business communities began in the mid-1970's. The aim of these studies, as is the case with most of the wide-area aerial surveys, was to utilize infrared thermography to provide the public with information on home heat loss. As mentioned earlier, one of the most attractive features of this type of survey is the large volume of information which can be collected over a short time period, at a low unit price per home surveyed. The information gathered is compiled and displayed in the form of thermograms for review by interested property owners. Public response to these programs has been better than expected and hopefully has helped to increase public awareness of the need for energy conservation practices.

Both the ground level and aerial surveys of heat loss from buildings are useful tools in qualitatively assessing infrared radiation from surfaces. However, there are many, both in the business and scientific communities, who wish to extend the limits of the current technology, to include not only qualitative, but quantitative estimations of heat loss from buildings. As a result, some controversy has risen over exactly how much quantitative or even qualitative information can be extracted from the thermograms obtained during IR radiation scanning surveys.

The discussion from this point on, will be limited to aerial remote sensing studies, since that is the focus of this report. However, many of the same interpretative problems are inherent to the ground surveys as well. Current technology for aerial remote sensing studies of rooftop heat loss entails the use of an IR scanner system which measures radiation in a given wavelength band chosen to minimize atmospheric interferences. For most systems, this wavelength band is from 8 to 14 μ m (comparatively, ground level infrared systems are usually sensitive to radiation in the 2-5 μ m band). IR radiation detected by the scanner (see complete discussion in Section 2.A) is recorded either on electromagnetic tape or photographic film, depending on the chosen system. Processing of the collected data usually results in the production of a thermographic image which displays the radiant "heat" energy from rooftops as shades of gray or as colors. These images do not directly display heat loss or even temperature, and only with proper and careful interpretation can heat loss information be inferred from the thermograms. Most users and manufacturers of IR thermography agree in principle to this fact, and when presenting the results of their studies, include technical discussions of the derivation of this conclusion. However, other factors, often overlooked, play an important role in the quantification of thermographic information. Environmental factors at the time of data collection, structural and material properties of the surface under study, type of scanner system used and orientation of the scanning aircraft must all be considered when attempting to determine actual roof surface temperatures.

As part of a study on the use of thermal imagery for evaluation of insulation and construction conditions, Tanis et al. (1976) present the results of an aerial survey of a large number of residential buildings. Interpretation of the aerial data consisted of producing a number of calibrated temperature "slices" by quantifying the data into discrete signal levels representing "apparent" temperature ranges. The ranges were individually imaged and photographed to highlight all surfaces in the same temperature range. These black and white temperature prints, it was concluded, provided "quantitative evidence of building surface temperatures and their variations." In producing these images, however, the assumption was made that the emissivities (i.e., ability of the material to radiate energy) of all the surfaces studied were constant and near unity. For metal surfaces with known low emissivities, individual temperature corrections were made.

Emissivity, however, is one of the variables which plays an important role in the determination of surface temperature and cannot be treated lightly in attempting to quantify heat loss. Indeed, emissivity values will change for each type of surface material studied and for each wavelength band considered. Jones et al. (1977), for instance, discuss emissivity (primarily in the 2-5.6 μ m range) and concludes that "extreme care must be taken when making comparisons of surface temperatures of different materials when an emissivity measurement has not been made" and "suggests that meaningful results ... may only be possible for surfaces of identical materials."

Other variables also exist and must be addressed. Borman et al. (1977) discuss the interpretation of data obtained from overflights of NASA centers. He reports that true surface temperature can be calculated from the effective radiation temperature when the surface band emittance is known. The given expression for this calculation does not take into account the atmospheric effects, roof orientation, or ventilation underneath the roof and assumes, for the energy losses of interest, that the band emittances are generally greater than 0.7. The report goes on to discuss heat loss determinations which are calculated from effective temperature ranges, surface conductance, surface band emissivity and ambient air temperature. Again, the atmospheric variables, angle of observation, roof geometry and ventilation effects are not considered. Included in the recommendations, however, is a statement that better methods of quantifying thermal imagery are needed and effects of surface emittance, accurate temperature discrimination, flight altitude, weather conditions, and time of day on quantitative heat flux determination are necessary for improved utilization of thermal imagery.

Brown et al. (1977) discuss the need to include the effects of attic ventilation, roof emissivity and roof pitch variations in determining roof temperature. Of particular significance in this work, is the development of a model used for calculating attic ventilation effects on residential heat loss analysis. Specifically, the authors demonstrated that there was not a strong correlation between apparent roof temperatures and insulation R - values (a measure of the resistance of a material to heat flow). Indeed, other factors were contributing to observed variations on the imagery. Roof pitch was found to have a substantial effect upon the apparent roof temperatures; notably, model calculations

showed a temperature change of 0.6°C resulting from a change in roof pitch from 1/3 to 5/6. Finally, attic ventilation was considered as a variable and it was found that when attic ventilation was taken into account, there was a marked improvement in the prediction, of attic R-values from aerial thermograms. Emissivity variations between houses were also considered important and the investigation of this problem is currently underway.

Brown (1978) reports on further study done to examine the possibility of using an IR scanning system in the 8-14 μm band to quantitatively estimate heat loss from buildings. He concludes that any attempt to calculate heat loss using aerial thermal imagery should consider the effects of attic ventilation, roof pitch, roofing material, and house type. He also stresses the need for accuracy in emissivity determination and points out that data collection under proper conditions (clear skies, calm winds, dry roofs and large temperature differences between interior and exterior surfaces) with carefully calibrated equipment is essential for optimum utilization of thermal data. In his most recent work, Brown (1979) reaffirms the importance of house style, roof pitch variations, and attic ventilation. He also states that care should be taken in noting water/snow/ice patches on flat roofs at this seems to be the major obstacle to proper interpretation of thermal images of these structures. Finally, Brown reports that model calculations show the temperature difference between houses with R-10 and R-20 insulation was 0.8°C which is detectable with present IR systems, thus suggesting that attic insulation information is available from current imagery.

Goldstein (1978) also reports in his study of the relationship of roof surface temperature and the properties of heat transfer and emitted infrared radiation, that there are many variables which must be considered when interpreting thermal data. He states that although emissivity changes do not have a major effect on actual roof surface temperature, they do have a significant effect on the apparent roof temperature as measured by an IR scanner. He further points out that local wind speed, sky temperature and roof ventilation may actually overshadow the influence of roof structure thermal resistance on the

surface temperature. He feels strongly that, at this time, application of the current technology is most valuable in finding discontinuities of roof surface temperature on a uniform surface, and that systems for measuring heat loss will work best with homogeneous, horizontal surfaces so that variations in the surroundings (trees, other roofs, etc.) will not affect the results. Comparison of roofs with varying thermal resistances should be possible at low wind speeds.

In an attempt to condense much of the information available on the current status of thermal imaging technology, the U.S. Department of Energy has sponsored two studies intended to stimulate the interest of potential users of the technology. Dick and Schmer (1978) have provided a "how-to" manual of technical information on the use of aerial infrared scanning systems, intended to familiarize users with the capabilities of the various systems. Shumaker et al. (1979) gives a more general, non-technical overview of the state of the technology as a whole. They also point out the need for additional study in order to realize the full potential of thermal survey technology and discuss some of the existing problems with interpreting survey data.

Finally, Van den Berg (1976) wrote in his report some time ago, that "where qualitative answers are satisfactory or where temperature differences in themselves are significant indicators of trouble, infrared devices make excellent diagnostic aids." Detection of moisture in insulation of flat roofs, determining the pattern of a power plant hot water effluent in a stream, detecting changes in agricultural growth and finding steam and hot water lines underground are discussed as some of the best applications of IR thermography. However, Van den Berg cautions that "IR thermography has its place, but is not a panacea for all the problems of our energy conscious public. When used with discretion and understanding of its shortcomings, it can be a very useful tool."

Three years later, these are still useful words for consideration by those interested in the benefits offered by infrared thermography.

Thus, the problems in measurement of heat loss by thermography are well documented in the literature (cf. Brown, 1978b and Evans, 1978). They include:

1. The effects of atmosphere and sky background on the signal observed at the scanner;
2. The need to know emissivities;
3. The lack of consistent material emissivities;
4. The lack of knowledge of how emissivity varies with angle of observation;
5. The effect of roof pitch and adjacent structure on the background radiation;
6. The effects of ventilation on heat loss; and
7. The interplay of several factors besides temperature in the loss of heat due to convective and conductive effects.

This report addresses and defines solutions for problems one through five. Atmospheric and sky background effects are discussed in Section 3. Emissivity and material identification techniques are discussed in Sections 4 and 5 respectively. The combined effects of emissivity, atmospherics and backgrounds are discussed in Section 6.

Potential solutions to problems 6 and 7 above are discussed in Section 7. These problems were considered to be more appropriate to future efforts and were not heavily stressed as part of this effort.

In finishing this section on the literature, we should point out that the literature discussed here addressed the broad topic of "thermography for heat loss". In the sections that follow pertinent literature will be treated where appropriate.

SECTION 3 *

ATMOSPHERIC AND BACKGROUND EFFECTS

In Section 2.B, we discussed several parameters (blackbody, v/H , step-wedge, etc.) important in properly interpreting thermograms. These parameters can all be (but are often, not) accounted for using most scanning systems. This section will discuss several additional parameters that affect the interpretation of thermograms. The atmospheric and background effects discussed here are largely scanner independent and although they have significant impact on thermogram interpretation, they are very seldom accounted for. We present in this section methods to measure each of the important parameters as well as the results of an experiment to test how well atmospheric, background and scanner related terms can be measured and accounted for.

3.A Theoretical Approach

To interpret the radiant energy reaching a point at any distance from the source, one must consider atmospheric or path effects; of prime concern is atmospheric transmission over the path lengths of interest. The atmospheric transmission window between 8 and $14\mu\text{m}$ is the most useful for earth observation work for a number of reasons. It encompasses the radiant energy peak of $9.5\mu\text{m}$ for objects near earth ambient temperature of 300°K . The transmission is quite high over the entire window, and the window is spectrally very broad, permitting integration over a sizable fraction of the total distribution.

Primary attenuation in the lower atmosphere is due to absorption by H_2O vapor, CO_2 and OH . These molecules absorb the radiation and re-radiate it at a rate which is a function of atmospheric temperature, thereby introducing two noise terms into the system.

These terms can be included in the expression we have defined as Equation 2.B-7 as follows:

$$W = \tau \epsilon W_T + W_A \quad (3.A-1)$$

where τ is the atmospheric transmission and W_A is the apparent radiant emittance from the air column between the source and sensor, as well as energy scattered

* This section summarizes the results of earlier work reported in detail in Schott 1977.

into the sensor. It is important to keep in mind that W_A and τ vary within the air column and as a function of atmospheric conditions on a given day.

Experimental evidence indicates that the atmospheric conditions controlling τ and W_A are generally stable over distances of several to tens of miles if no major climatological influences are present (e.g., large bodies of water, major topographic changes). Atmospheric conditions affecting τ and W_A do occur over time. Experimental data indicate that significant changes occur over 3 to 5 hours under daytime conditions. We would also expect rapid changes in conditions just after sunset with more stable conditions occurring later in the night when heat loss measurements are usually made. Typical ranges for τ and W_A for typical flight altitudes are 0.85 to 0.95 and 0.002 W/m^2 , to 0.008 W/m^2 , respectively. We would expect τ to decrease and W_A to increase as altitude and humidity increase (e.g., a 10% change in altitude results in about a 1% change in τ). To provide some perspective on these variations, 0°C corresponds to a W_T value of 0.011 W/m^2 . Some simple calculations with these numbers yield the following insights: the remotely-sensed energy can be more or less than the actual energy; one-percent change in τ results in an 0.6°C temperature correction; a 10% change in W_A will result in the same required temperature correction. We should further note that a change in τ (for example, a decrease) is generally offset to some extent by a compensating change in W_A (i.e., W_A will increase). Therefore, slight variations or errors in τ will tend to be reduced by corresponding variations or compensating errors in W_A . It is particularly important to know τ and W_A if imagery collected at different times are to be compared. If τ and W_A are not accounted for, path induced contrast differences will be neglected, making precise data comparison very difficult.

In addition to the radiant energy from the source itself, a certain amount of energy will be reflected from the ground. This energy comes from the sky. Skylight reflection effects can be expressed as $W_S \tau R$ and included in Equation 3.A-1 yielding

$$W = \tau W_T + W_A + W_S \tau R \quad (3.A-2)$$

where W_S is the radiant energy from the sky incident on the surface observed, and can be associated with an equivalent sky temperature T_s . R is the surface reflectance of the object observed.

Skylight irradiance comes from scattered solar radiation, radiation emitted from components of the atmosphere (especially the ozone layer and H₂O vapor); and energy from the earth reflected by the atmosphere. All these effects combine to give the sky an apparent radiometric temperature as viewed from the ground. For our purposes, this is the blackbody temperature equivalent, T_s , associated with the amount of energy incident on the source over the bandpass of interest. T_s can vary considerably with sky conditions from about 300°K for heavy overcast to well below 250°K for clear sky conditions.

In evaluating the range of values for the reflectance terms, we recognize that reflection is dependent on look angle. In addition, we have mentioned that W_A and τ are dependent on the length and composition of the atmospheric path between the source and observation point. To recognize this dependence in Equation 3.A-2, the functional dependence on θ and h will be added to designate angular and height dependence, respectively, where h is the height of sensor above terrain,

$$\theta \text{ is look angle measured from the vertical and}$$

$$W(h, \theta) = \tau(h, \theta) \epsilon(\theta) W_T + W_A(h, \theta) + \tau(h, \theta) W_s R(\theta) \quad (3.A-3)$$

The energy paths associated with this expression are shown in Figure 3.A-1.

Limiting our discussions for the moment to vertical viewing, ($\theta = 0$) results in

$$W(h) = \tau(h) \epsilon W_T + \tau(h) W_s R + W_A(h) \quad (3.A-4)$$

Letting $W(0)$ be the energy from the ground as it would be measured vertically at zero altitude, Equation 3.A-4 reduces to

$$W(h) = \tau(h) W(0) + W_A(h) \quad (3.A-5)$$

$$\text{where} \quad W(0) = \epsilon W_T + W_s R \quad (3.A-6)$$

FIGURE 3.A-1 ENERGY PATHS IN THE 8-14 μ m BAND-PASS
ACCORDING TO EQUATION 3.A-3

$$W(h, \theta) = \tau(h, \theta) \epsilon(\theta) W_T + W_A(h, \theta) + \tau(h, \theta) W_S R(\theta) \quad (3.A-3)$$

If $W(h)$ and $W(0)$ are known for a set of observed values, then by least squares analysis of Equation 3.A-5, $\tau(h)$ and $W_A(h)$ can be calculated. $W(h)$ and $W(0)$ represent the radiant energy observed by the sensor at flight altitude and ground level, respectively. In practice, the ground level measure is obtained by extrapolating a plot of altitude-versus-temperature to zero altitude using data collected over the same point at a series of altitudes, where radiant energy is converted to apparent blackbody temperature.*

If we ~~once~~ again consider the angular viewing effects, Equation 3.A-5 becomes

$$W(h, \theta) = \tau(h, \theta) W(0, \theta) + W_A(h, \theta) \quad (3.A-7)$$

where

$$W(0, \theta) = \epsilon(\theta) W_T + W_S R(\theta) \text{ and} \quad (3.A-8)$$

$$\tau(h, \theta) = \tau(h, 0) \exp (1/\cos \theta) \text{ and} \quad (3.A-9)$$

$$W_A(h, \theta) = W_A(h, 0)/\cos \theta \quad (3.A-10)$$

These equations result from the increase in absorption with path length (Eq. 3.A-9) and the increase in atmospheric radiation with path length (Eq. 3.A-10). Since the path length increases as $1/\cos \theta$ for slant viewing and the effects on atmospheric emissions should be very nearly linear for small increases in path length through a given medium, Equation 3.A-10 is derived. Note that this assumption of linearity is only valid for increase due to slant viewing through a known atmosphere and is not necessarily valid for an overall increase in path length.

If observations were made at the same altitude of a given point through two different look angles, one of which may be taken as vertical for convenience, then Equations 3.A-4, 3.A-7 and 3.A-8 may be combined to yield

$$\begin{aligned} W(h, 0) = m W(h, \theta) - m(h, \theta) W_S R(\theta) - m W_A(h, \theta) \\ + \tau(h, 0) W_S R(0) + W_A(h, 0) \end{aligned} \quad (3.A-11)$$

*These measurements are made over water because it is free of background obstructions and has well-defined emissivity.

where

$$m = \frac{\epsilon(0) \tau(h, 0)}{\epsilon(\theta) \tau(h, \theta)} \quad (3.A-12)$$

Recognizing this as a straight line in the form,

$$W(h, 0) = mW(h, \theta) + I \quad (3.A-13)$$

and solving for W_s in terms of m and I yields

$$W_s = \frac{I + mW_A(h, \theta) - W_A(h, 0)}{\tau(h, 0) R(0) - m\tau(h, \theta) R(\theta)} \quad (3.A-14)$$

Least squares analysis of Equation 3.A-13, with input data consisting of apparent temperatures (converted to radiant energy) measured along a line viewed vertically, and then at a slant angle, will yield a measure of apparent sky temperature as viewed from the ground from Equation 3.A-14.

We have assumed that the apparent temperature of the sky is a constant with respect to angle of observation. In general, this is not the case; rather, the zenith sky appears colder than the sky near the horizon because the atmosphere viewed vertically has fewer radiators. In order to minimize potential errors in measured sky temperature, the analysis discussed above can be conducted for a number of look angle combinations, and a simple relationship between T_s and θ can be developed.

Another solution would involve use of a vertical-viewing, upward-looking radiometer on board the aircraft. Measurement of vertical sky temperature at a number of altitudes and extrapolation to the apparent temperature of the nadir sky as viewed from the ground would eliminate one unknown in Equation 3.A-11. The equation could then be solved for the sky temperature at look angle θ (i.e., T_s associated with $R(0)$ would be known and T_s associated with $R(\theta)$ would be unknown).

Rewriting Equation 3.A-3 as

$$W_T = [W(h, \theta) - \tau(h, \theta) W_s R(\theta) - W_A(h, \theta)] / \epsilon(\theta) \tau(h, \theta) \quad (3.A-15)$$

we find

$W(h, \Theta)$	is a measured value
$W_A(h, \Theta)$	is obtained from Equation 3.A-10 and least squares analysis of 3.A-5,
$\tau(h, \Theta)$	is obtained from Equation 3.A-9 and least squares analysis of 3.A-5,
W_s	is obtained from Equation 3.A-14
$R(\Theta)$ and $\epsilon(\Theta)$ are tabulated values for water.	

It should therefore be possible to measure the absolute value of surface waters based on the theories developed thus far. The next section contains procedural approaches for collection of the necessary input data to solve for the values in Equation 3.A-15.

3.B Calibration Procedures: Profile Technique (Angular Technique)

Our concern at this point is in defining procedures for collecting sufficient input data to permit the use of the theoretical procedures under discussion. We will neglect, for simplicity, signal processing through the sensor and assume that apparent blackbody radiometric temperature can be measured at the sensor location by converting radiant energy to equivalent blackbody temperature. The procedures for accomplishing this are contained in Section 2.B.

As shown in Equation 3.A-5, the input data necessary to calculate the transmission term $\tau(h)$ and the additive target-independent energy from the atmosphere $W_A(h)$ consists of $T_B(h)$ and $T_B(0)$ corresponding to $W(h)$ and $W(0)$. $T_B(h)$ is simply the apparent blackbody temperature measured at altitude h with look angle $\Theta = 0$. $T_B(0)$ is the apparent temperature measured at the surface of the water. This value cannot be measured directly but is obtained by a profile technique which involves a simple extrapolation process for data collected at a series of altitudes to a zero altitude case obtained by consecutive flights over the same target (cf. Schott 1977). A target consists of an area of uniform temperature either large enough to be directly below the aircraft during the profile or within about 10° from the nadir and distinct enough to be identifiable on the profile images. At angles much larger than 10° , the assumption of vertical viewing during the profile no longer holds.

The minimum data input required for Equation 3.A-5 is $T_B(h)$ and a corresponding $T_B(0)$ for at least two points at differing temperature. Ideally, these data consist of a set of approximately five data points covering as wide a temperature range as possible. Figures 3.B-1 and 3.B-2 indicate how $T_B(h)$ and $T_B(0)$ could be obtained for a number of different temperatures. Figure 3.B-3 is a series of plots of apparent temperature versus the altitude at which it was measured for several points in the Hudson River.

The input data necessary to calculate W_s , the sky light radiance term, come from the solution of Equation 3.A-13 requiring $T_B(h, 0)$ and $T_B(h, \theta)$ as inputs. These values are the apparent temperature observed at the same point through two look angles where one look angle is chosen as zero degrees for convenience. (Note also that Equation 3.A-5 can be solved directly for W_s i.e., a one-point solution is available). The minimum data required to solve Equation 3.A-13 consists of two data sets composed of $T_B(h, 0)$ and $T_B(h, \theta)$ for two distinct points. In general, a number of points with a large range in temperature should be used to solve for m and I in Equation 3.A-13. These data can be collected by flying two parallel flight lines and allowing for some sidelap. This procedure is often used to obtain complete target coverage and would add little or no time to most collection efforts. Figure 3.B-4 illustrates how these data can be obtained. Figure 3.B-5 shows the relationship between the physical collection process and the theoretical equations describing the procedure.

3.C Evaluation of the Profile Technique (Angular Technique)

A ground-truth program was used to evaluate these radiometric calibration techniques. This effort involved aerial overflights of a boat anchored at a series of positions in the Hudson River, both within and beyond the thermal plumes of various power plants.

With the boat anchored at a given position, readings were made on the upstream (downstream if flow was upstream in the estuary) side of the boat. Measurements consisted of temperatures recorded from a submerged thermistor (nominally at a depth of 6 in.) and from a Barnes PRT 5 Radiometer. During each flyover, approximately ten readings were recorded and averaged to predict the temperature at a point. To ensure unbiased data, all surface measurements

FIGURE 3.B-1 THERMAL IMAGES OBTAINED DURING A PROFILE. AREAS OF EQUAL TEMPERATURE ARE INDICATED WHERE APPARENT TEMPERATURE READINGS COULD BE MADE.

1500'

$$W(h,0) = \tau(h,0) \epsilon(0) W_T + \tau(h,0) R(0) W_S + W_A(h,0)$$

1000'

$$W(\frac{2}{3}h,0) = \tau(\frac{2}{3}h,0) \epsilon(0) W_T + \tau(\frac{2}{3}h,0) R(0) W_S + W_A(\frac{2}{3}h,0)$$

500'

$$W(\frac{1}{3}h,0) = \tau(\frac{1}{3}h,0) \epsilon(0) W_T + \tau(\frac{1}{3}h,0) R(0) W_S + W_A(\frac{1}{3}h,0)$$

0'

$$W(0,0) = \epsilon(0) W_T + R(0) W_S$$

FIGURE 3.B-2 ILLUSTRATION OF HOW THE PROFILE DATA IS COLLECTED

FIGURE 3.B-3 PLOT OF TEMPERATURE VERSUS ALTITUDE ILLUSTRATING ATMOSPHERIC VARIATION IN OBSERVED TEMPERATURE FOR FOUR PROFILES

FIGURE 3.B-4 EXAMPLE OF PARALLEL FLIGHT LINES OVER A POWER STATION SHOWING THE CHANGE IN LOOK ANGLE FOR A GIVEN GROUND POINT.

$$W(h, \theta) = \tau(h, \theta) \epsilon(\theta) W_T + \tau(h, \theta) R(\theta) W_S + W_A(h, \theta)$$

FIGURE 3.B-5 EXAMPLE OF ENERGY EQUATIONS FOR A GIVEN POINT FOR A CHANGE IN LOOK ANGLE

$$W(h,0) = \tau(h,0) \epsilon(0) W_T + \tau(h,0) R(0) W_S + W_A(h,0)$$

were made by independent consultants and surfaces/data were withheld until aerial results had been delivered to the New York State Energy Research and Development Authority (NYSERDA). The surface radiometer was calibrated in the field under prevailing atmospheric conditions to ensure that all measurements were absolute surface temperature measurements. The ground truth portion of this test is reported in Wormser Scientific Corporation Report dated 9/24/76.

The main survey took place on September 24, 1976, with the boat anchoring at eight positions throughout the day. The aircraft flew over each position four times, permitting 32 data-comparison points for the total survey. Because the boat was covered with aluminum foil, it had a low emissivity and could be located as a "cold" spot on the image. Surface temperatures were predicted using the calibration technique discussed above. Data were also collected at eight positions for five overflights on July 8, 1976.

Table 3.C-1 presents the results of the data correlation for September 24, 1976. The mean and standard deviations of the absolute value of the difference between the aerial and surface data are presented. Radiometric surface data were used because they are a more accurate measure of the actual surface temperatures than are the submerged thermistor data. Comparison of submerged (6 in.) thermistor data and aerial data showed a mean difference of 0.51°F with a standard deviation of 0.46°F . Also included is a correlation of radiometric temperatures, to which no atmospheric correlations have been applied, with the surface data. Table 3.C-2 contains the results of the July 9, 1976 survey.

When the July and September data are combined, a mean error of 0.70°F is obtained with a standard deviation of 0.59°F (Angular Technique). This compares with a mean error of 3.23°F with a standard deviation of 1.25°F if only internal system calibration is used. Figure 3.C-1 illustrates the precision of the calibration technique and the limitations of using only internal scanner calibration. The figure shows the surface radiometer data plotted against the calibrated (#) and uncalibrated (0) scanner data. The data, which have been corrected for atmospheric and background effects, show a very close fit within the 1°F error bars. The data using only the internal scanner calibration show sizable errors and are generally less than the actual temperature. Note that

TABLE 3.C-1

Comparison of Surface and Aerial Data
for 24 September 1976 (°F)

	<u>Surface Radiometer and Uncorrected Airborne Scanner</u>	<u>Surface Radiometer and Angular Technique</u>
Mean of the absolute value of the temperature difference be- tween boat and aircraft	4.19	.55
Standard deviation of ΔT	1.22	.57

TABLE 3.C-2

Comparison of Surface and Aerial Data
for July 9, 1976 (°F)

	<u>Surface Radiometer and Uncorrected Airborne Scanner</u>	<u>Surface Radiometer and Angular Technique</u>
Mean of the absolute value of the temperature difference be- tween boat and aircraft	2.66	.80
Standard deviation of ΔT	1.27	.57

FIGURE 3.C-1 COMPARISON OF SURFACE AND AERIAL TEMPERATURE MEASUREMENTS
(The lines represent a 1°F error envelope.)

Temperature measured using the
"Angular Calibration Technique" °F.

31

90,90

Temperature measured using the
Thermal Scanner Calibration but
without atmospheric correction °F.

90,90

65,65

Temperature measured at the surface °F.

65,65

Temperature measured at the surface °F.

this is generally the case but that a temperature higher than the true surface temperature can be detected by airborne systems under certain atmospheric and background conditions.

One shortcoming to the angular technique is a requirement for extra data to permit calibration and some additional data processing. Neither the time nor the cost is appreciable; however, the data must be properly collected. Some improvements in accuracy could be expected if data collection were modified to facilitate analysis using the angular technique. Major improvements in water temperature measurement cannot be expected because temperatures predicted from the air approach the accuracies obtainable by surface measurements.

The data correlation results presented in this section represent a major advance in airborne radiometric measurement of water surface temperature. Measurement accuracies essentially as good as surface measurements are demonstrated.

The data collection procedures involve only minor variations in standard collection practices requiring approximately fifteen additional minutes of flight time. Data processing can all be done on a desk-top computer.

The net result of these conclusions is that a fully airborne approach to measure water surface temperatures, with accuracies comparable to those obtained from surface measurements, is an operational reality. In addition, these results were obtained through use of an outside consultant for acquisition of ground-truth data, thus precluding any bias.

These results also serve to demonstrate the utility of the profile calibration technique in calculating the atmospheric and background terms affecting the signal reaching an airborne system. They indicate that, for flat surfaces whose emissivities are known (such as water), surface temperatures can be measured quite precisely using only airborne systems. In most instances the rooftop emissivities are not well known over the 8-14 μ m bandpass used in data collection. The next section will discuss procedures developed at Calspan for measurement of emissivity of building materials. Section 6.A discusses procedures for accounting for sloped roof effects.

SECTION 4

EMISSION

The measurement of roof temperature values using infrared techniques is dependent on the knowledge of emissivity. Emissivity is a measure of how well a material radiates energy and is dependent on the material being observed. One objective of this program was to define the values and the variability in values of emissivity of common roofing materials.

4.A Emissivity Measurements

Several methods for measurement of the emissivities of materials exist. In order to discuss the utility of the methods, we must first clearly define the nature of the measurement we are interested in. Emissivity values are measured and commonly reported as hemispheric or directional values. Hemispheric values represent the emissivity of a source radiating into a hemisphere where as directional values represent the emissivity of a source radiating (or observed) over a small solid angle γ . (γ is measured from the normal.) Hemispheric or directional measurements can both be made over the complete spectrum (usually 1-20 μ m) or over discrete wavelength intervals. (A more detailed discussion can be found in Hudson, 1969.) Our interest was in directional measurements over the 8-14 μ m spectral bandpass used by scanning systems. In particular, since most of the surfaces of interest can be assumed Lambertian (i.e., showing little or no change in effective ϵ with angle to γ values of 60°), we were particularly interested in 8-14 μ m normal emissivity values. Gubareff (1960) conducted an extensive review of the literature on radiation properties. Prior to that time, there were essentially no useful data on 8-14 μ m emissivities of roofing materials. The spectral scan type data that do exist are primarily obtained by employing Kirchoff's law ($\epsilon = 1-R$) to data obtained in reflectometers. These data are useful only for polished surfaces which reflect the columnated monochromatic incident energy into a small, easily collected cone of energy. The diffuse roofing surfaces we are interested in would spread such an incident beam over large acceptance angles requiring integrating spheres for collection. Use of integrating spheres introduces background effects which to-date have proven very difficult to deal with. Buettner and Kern (1965) describe

an emissivity box used to make normal emissivity measurements in the 8-14 μ m spectrum. The system used, however, employed many approximations of perfect reflecting or perfect emitting surfaces. The corrections for these non-perfect surfaces, in addition to certain other limits to their approach, indicated that the precision of such an instrument might not be sufficient for our needs. Lorenz (1966) used an approach which called for the measurement of hemispheric sky radiance, and the radiance from a sample at known temperature. His calculations of emissivity, however, appear to incorporate certain background terms as well as requiring quite extensive efforts to measure the hemispheric sky radiance. Certain instrument designs commonly used for measurements of total normal emissivities could conceivably be modified for 8-14 μ m measurements (e.g., the Gier Dunkle DB100 reflectometer approach). The limit with most of these systems is that the signal level required to operate the instruments over limited band widths is not readily available. Because of this problem, most instrument designs in this category were not seriously evaluated. One interesting approach employed by Brown and Young (1975) used a Fourier transform spectrometer and involved comparing spectral scans of samples and blackbodies run at different temperatures ranging from liquid nitrogen temperatures to near ambient values. The scientific integrity of this approach appeared to be the best of any approach reviewed. We have some concern that the expense of solving the engineering problems might be prohibitive. In addition, changes in emissivity due to changes in material properties might be expected over the large ranges in temperature employed.

In summary, most of the approaches considered for measurement of emissivity did not measure the 8-14 μ m directional emissivity we were concerned with. The devices which measured or could be adapted for 8-14 μ m directional measurements were ruled out because of theoretical questions, limited precision or inability to handle roofing materials. It, therefore, appeared most suitable to design and build a device to measure the 8-14 μ m directional emissivity of roofing materials.

4.B Calspan Approach

Several theoretical and engineering schemes were employed before deciding on the final instrument design and operating procedure. Only the final technique used for the measurements presented as part of this study will be discussed here.

4.B.1 Theoretical Procedures for Measurement of Emissivity

The technique utilized involves an approach that attempts to account for the background terms without using any assumptions of blackness or perfect reflection. The technique involves use of a cell or cavity with a constant background radiance. The surface to be studied is placed at one end of the cavity and observed from the other. The temperature of the source (material under study) is then varied while being monitored by contact thermistors and by an 8-14 μ m infrared detector at the opposite end of the cell.

The contact temperature can be converted to the equivalent 8-14 μ m blackbody emittance using the procedures defined in Section 2.A. The apparent radiometric temperature recorded by the detector can also be converted to the observed emittance from the material. This observed emittance can be expressed as

$$W_O = \epsilon_{\Delta\lambda} \tau W_T + R W_B + W_A \quad (4.B-1)$$

where:

W_O	is the observed emittance
$\epsilon_{\Delta\lambda}$	is the 8-14 μ m emissivity of the surface observed
τ	is any attenuation that might exist in the system
W_T	is the blackbody emittance associated with the measured surface temperature.
R	is the 8-14 μ m reflectivity of the surface
W_B	is the background emittance reaching the surface
W_A	is any energy that might reach the sensor independently of the source.

If we vary W_T by changing the temperature of the surface we can plot W_T against W_O with the slope being $\epsilon_{\Delta\lambda} \tau$. If we run this same experiment for

a surface with a known emissivity then the ratio of the slopes will be the ratio of the emissivities for the two surfaces. Since one of these values is known, the other can be calculated. The advantages of this approach are that the background is neither measured nor assumed due to a perfect absorber or reflector. It is only assumed constant for the duration of the experiment. The terms τ and W_A are expected to be very close to 1 and 0 respectively; however, it is not necessary using this approach to make those assumptions. In addition, this approach does not employ Kirchoff's Law. This frees us from any of the limiting conditions that might apply to employing Kirchoff's Law over a discrete bandpass.

4.B.2 Instrument Design and Operation

The emissometer was specifically designed to draw on the theoretical techniques discussed in the previous subsection. Figure 4.B-1 is a diagram of the instrument. The detector was mounted in the background cavity looking vertically at the sample. The entire instrument was operated in a temperature controlled room to maintain the background cavity at fixed temperature. Radiation baffles with highly reflective surfaces towards the sample were employed to minimize radiational exchange between the cavities. An insulation panel closed the observation port between measurements to prevent convective heat exchange. The temperature of the lower cavity could be varied to change the sample temperature. The sample was freely suspended in the cavity and allowed to come to thermal equilibrium. Thermistors attached to the sample permitted calculation of W_T . W_O could be calculated from the radiometer signal when the insulation panel was removed. The background cavity temperature was monitored to ensure stability during the operation of the instrument.

In practice, low ($\sim 3^\circ\text{C}$), ambient ($\sim 18^\circ\text{C}$) and high ($\sim 50^\circ\text{C}$) temperature values of W_O and W_T were calculated for the blackbody and the samples. The

FIGURE 4.B-1 SCHEMATIC DIAGRAM FOR THE EMISSOMETER (CROSS-SECTION)

slope of the straight line fit between W_T and W_O was then calculated for the blackbody and for each sample. (The blackbody was run periodically as a reference). The slope is equal to $\tau\epsilon_s$ for the sample and $\tau\epsilon_b$ for the blackbody (cf. Equation 4.B-1). The ratio of the slopes yields ϵ_s/ϵ_b which when multiplied by the blackbody emissivity (0.94 for our standard) gives the 8-14 μ m normal emissivity of the sample.

4.B.3 Emissivity Results

The intent of the emissivity experiments was to design and build an instrument to obtain 8-14 μ m directional emissivities of common roofing materials. The real need of course was to define the range and variability of emissivities associated with roofing materials.

The error in the emissivity measurements associated with the instrument was carefully checked by making periodic measurements on a blackbody reference sample ($\epsilon = 0.94$)*. The error in the emissivity measurements is estimated to be ± 0.02 based on an error of ± 0.016 in the blackbody measurements. The total expected error is slightly larger than the blackbody error because the blackbody value is used in the final computation of emissivity and therefore, the error associated with it must also be accounted for. The results of the emissivity measurements made to date are contained in Table 4.B-1. They indicate that a wide range of values in emissivity is possible depending on roofing material, but that the variation within a given material type is generally small. The variation for instance in the 14 different asphalt shingles studied was ± 0.018 (Std. deviation). These shingles incorporated variability in age, color and weight. Detailed studies on other roofing materials has not yet been undertaken. This is a particularly promising result because it indicates that knowledge of general material types should be sufficient to yield emissivity values. In most material groupings, most of the error within the group can be explained by the measurement error. Variations due to aging (i.e., stone removal) of asphalt shingles do not appear to be significant at this point. The only significant aging effect was noted with copper roofing material. Because new

*The term blackbody as used here is an engineering term rather than, strictly speaking, a true blackbody ($\epsilon=1$) which for engineering purposes does not exist.

TABLE 4.B-1

EMISSION VALUES FOR COMMON ROOFING MATERIALS

<u>ASPHALT SHINGLES</u>			<u>MISCELLANEOUS MATERIALS</u>		
<u>Sample #</u>	<u>Color</u>	<u>ϵ</u>	<u>Sample #</u>	<u>Material</u>	<u>ϵ</u>
102	White	0.93	304	Red clay tile	0.82
104	Grey	0.89	301	Oxidized Copper	0.95
105	Lt. Grey	0.93	321	Galvanized Metal	0.49
107	Grey	0.90	305	Plexiglass	0.80
112	Red	0.90	307	Glass	0.79
113.1	Red	0.89	116	Plywood	0.88
113.2	Black	0.89	210	Yellow Fiberglass	0.89
114	Black	0.89	103	Concrete	0.86
115	White	0.90	303	Concrete (Painted)	0.94
201	White	0.93	106	Lt.Wt. Roofing Felt	0.92
202	Brown	0.90	204	Hvy.Wt. Roofing Felt	0.88
205	Grey	0.89	320	Hvy. Felt w/Tar	0.88
206	Grey	0.92	*322	Full stones w/Tar	0.95
308	Brown	0.91	*323	Partial Stones w/Tar	0.84
			*306	Slag Roof	0.90
Mean ϵ for asphalt = 0.91					
σ for asphalt = 0.018					
<u>ASBESTOS SHINGLES</u>			<u>SLATE SHINGLES</u>		
<u>Sample #</u>	<u>Color</u>	<u>ϵ</u>	<u>Sample #</u>	<u>Color</u>	<u>ϵ</u>
109	White	0.92	108	Grey	0.83
110	Grey	0.89	302	Red	0.84

* Preliminary measurements only, due to difficulty making small samples, variability and poor conductivity.

copper roofing is quite uncommon, we would not expect this to be a problem and the value measured for oxidized copper can be commonly used. The effects of view angle were studied for several samples and appear in most cases to be below our resolution limits. Exceptions to this occur for slate, galvanized metal, glass and possibly in certain cases, for tar.* The only major problem in associating material type with emissivity which has been encountered thus far is with stone on tar commercial-type roofs. The initial measurements are not conclusive, but it appears as though variations due to the extent of stone/tar viewed and possibly due to the type of stone (e.g., slag rather than limestone) used may be important. This potential problem requires further investigation as do the potential problems associated with variation in emissivity with look angle and material weathering.

* The limited use of these materials for roofing indicated that greater emphasis should be placed on normal emissivity measurements until more sensitive instruments for angular measurements could be developed.

SECTION 5

MATERIAL IDENTIFICATION

As indicated in the previous section, material identification is one of the primary requirements for aerial measurement of temperature using the approach we are attempting to evaluate. It is the key to finding emissivity values. In this section, we will discuss two possible procedures which were evaluated for aerial identification of material types. The first procedure involved photometric analysis of daytime aerial photography. The second approach utilized a combination of nighttime 3-5 μ m and 8-14 μ m imagery.

5.A. Photometric Technique

The photometric analysis technique* is a unique approach which permits a daytime aerial color image to be used as a photometer to measure the spectral reflectance of the objects imaged (cf. Piech et al, 1974). These reflectances are then used as input data to a multi-variate discriminant analysis used to predict material types.

5.A.1 Photographic Effects

The photometric information stored on a daytime color photograph is contained in density space. The density** in each spectral band (red, green and blue) of the color imagery can easily be read using a densitometer. These density values are dependent on the type of film, photographic processing, camera settings and the amount of light (exposure) reaching the film from each object imaged. In order to obtain exposure values a density versus log exposure (D-Log E) curve is used.

A D-Log E curve is generated using a sensitometric control wedge which is put on the leader of each roll of film. This wedge typically consists of a series of twenty-one steps where each step is formed by increasing the log of the exposure used to form it by a fixed amount over the previous step. After the film is processed, it is a simple matter to read the spectral density

* U.S. Patents Nos. 3,849,006 and 4,037,048

** Density = - Log Transmission

of each step and plot it against the log of the exposure that step received. This process generates a D-Log E curve for each spectral band permitting the exposure for any point to be calculated from its density value.

The exposure values measured in this way on a photographic image must also be corrected based on their position in the image format. The exposure on the image decreases away from the center due to the collection optics of camera systems. This effect is called fall-off. For the 70mm Hasselblad cameras used in this study, the correction simply involves correcting the measured exposure by a factor of $1/\cos^3 \theta$ for the angle θ from the nadir to the observation point.

5.A.2 Atmospheric Effects (Photographic)

The exposure obtained through the D-Log E curve must still be related to reflectance values. This correction is important because exposure depends on meteorological conditions, altitude of measurement, and illumination conditions; such as, proportion of sunlight to skylight, and the amount of air light (the contribution to exposure by illumination scattered to the camera by the air column beneath the camera). These effects are depicted in Figure 5.A-1.

All of these effects can be approximately coupled into three parameters for a given spectral band: α , α' , and β . The parameter α is proportional to atmospheric transmittance and total (sunlight + skylight) irradiance; α' is proportional to atmospheric transmittance and skylight irradiance; and β is proportional to the amount of air light in the scene. The exposure, E , in sunlight of an object with reflectance R is

$$E = \alpha R + \beta \quad (5.A-1)$$

whereas the exposure of the same object in shadow, E' , is

$$E' = \alpha' R + \beta, \quad (5.A-2)$$

The (α , α' , β) parameters can be determined using a shadow calibration procedure called the Scene Color Standard (SCS) technique (Piech et al., 1974). Calibration is accomplished by densitometry of the illumination discontinuities

FIGURE 5.A-1 ATMOSPHERIC AND ILLUMINATION EFFECTS INVOLVED
IN ESTABLISHING THE EXPOSURE OF A SURFACE

at shadow edges. In sunlight just outside a shadow, the exposure E is given by Equation 5.A-1. Just inside the shadow, the exposure E' is given by Equation 5.A-2. Equations 5.A-1 and 5.A-2 yield

$$E = \alpha/\alpha' E' + \beta(1-\alpha/\alpha') \quad (5.A-3)$$

Equation 5.A-3 is a linear relationship between E and E' with slope α/α' and intercept $\beta(1-\alpha/\alpha')$. Two shadows determine the slope and intercept, and hence, β and α/α' . In practice, a number of shadows are analyzed, and a least squares fit is made to the data. Figure 5.A-2 shows typical calibration curves for calibration of a color image at a scale of 1:40,000.

The essential measurement and atmospheric conditions have now been determined. One aspect remains: that of establishing an absolute level of reflectance, akin to laboratory use of a magnesium oxide standard. A concrete scene element in sunlight (e.g. roadway) is usually used to establish the value of α and complete the calibration. These elements are used as: (1) their reflectances are spectrally flat; (2) their reflectances remain constant over the year; and (3) their reflectance can be easily estimated or measured. Other objects more appropriate for a particular survey can, of course, be used.

Under conditions where only reflectance ratio values are required, it is not necessary to know the reflectance of a scene element. Instead, the exposure values in one spectral band are plotted against the exposures in another band for a range of flat reflectors. The points obtained are then fit to a straight line in an analysis similar to that shown in Figure 5.A-2 for obtaining beta. The slope of the line thus obtained is equal to the ratio of the alpha values in the two bands. In practice, a slight correction is made to this value to account for the fact that most targets generally assumed spectrally flat are not actually uniform reflectors. Using the relative alpha values obtained in this manner, the reflectance ratios can be obtained. Furthermore, if the reflectance of a terrain object in any one band is known then the absolute alpha value for the band can be obtained as described above. The remaining alpha values can then be obtained from the alpha ratio values.

FIGURE 5.A-2 TYPICAL CALIBRATION CURVES FOR A COLOR IMAGE AT A SCALE OF 1:40,000. THE PARAMETER "ILLUM RATIO" IS $\delta \alpha'$. (CF. TEXT).

One minor point needs to be added for completeness. The skylight irradiance inside and outside the shadow is only some portion of the sky dome, k , due to solid angle shielding by the shadowing object. The factor k can be easily determined from metric considerations. In practice, at high altitudes, only larger buildings suffice for densitometry, and k is practically constant for all the structures utilized. The factor α' in Equations 5.A-2 and 5.A-3 should therefore be replaced by $k\alpha'$ and interpretation of the resulting values of slope and intercept so modified.

At an altitude of 10,000 feet, β can be equivalent to about a 5-10 percent reflector. At low altitudes, β will usually not decrease much below a 2-3 percent equivalent reflector because of camera flare, which is included in the additive light factor represented by β . It must be emphasized that the actual values of β will depend strongly on meteorological conditions, the spectral band (bandwidth, central wavelength) in which the measurement is made, and the flare characteristics of the instrument utilized. Because of the wide variation of β (and also α and α') with atmospheric, illumination and measurement system variables, exposures must be carefully reduced to reflectances before meaningful environmental assessments can be made.

A photointerpretation console which enables the interpreter to calibrate color film quickly and accurately has been fabricated for the Reconnaissance Applications Section, Rome Air Development Center, United States Air Force (cf. Walker et al. 1974). A similar console is available at Calspan's Buffalo facility. Figure 5.A-3 contains a schematic of the experimental photointerpretation console. The console provides the image interpreter with all of the capabilities he presently utilizes; i.e., (1) a variable illumination light table and (2) zoom stereo magnification with reticules and scales for mensuration in a convenient location. However, in addition, (3) a micro-macro densitometer capability, (4) a desk calculator and display capability and (5) a CRT color display capability are provided to facilitate removal of atmospheric effects and present reflectance ratio information to the interpreter. To generate the reflectance ratio information, another light table (6) is required to photographically copy and develop (7,8) the spectral ratio imagery which is then displayed to the density slicing and color encoding vidicon (9)

FIGURE 5.A-3 THE EXPERIMENTAL PHOTOINTERPRETATION CONSOLE.
THE CONCEPT AND DEVELOPMENT OF THE CONSOLE WAS
SPONSORED BY ROME AIR DEVELOPMENT CENTER,
U.S. AIR FORCE

for display on the color CRT, through a control panel (10).

5.A.3 Classification Approach: Multivariate Statistics

In order to classify roofs according to material type, a multivariate discriminant analysis is used. This type of approach uses a training set to describe an n-dimensional probability density distribution for each material type, where n is the number of discrimination parameters. For example, if we use the red, green and blue reflectances, n is equal to 3. These reflectances can be viewed as defining a point or vector in three dimensional space. If we have a number of vectors for the same material (selected as part of the training set), then the multivariate discrimination is based on those vectors. It will provide an output which consists of the category (material type) to which a vector should most probably be assigned. Because we train the classifier with reflectance data rather than raw density or exposure values, the classifier can be used in training and operating the classification technique on any calibrated data set. A more detailed discussion of the multivariate approach is contained in Morrison (1967).

5.A.4 Photometric Results

A preliminary classifier was developed using a training set consisting of approximately 150 surfaces. These surfaces represented both residential and commercial roofs including distinct categories. Densitometric measurements from the image of each surface were converted to reflectance values using the procedures discussed in the previous sections.

Using these data, classifiers were developed for the training set. Reflectance values, reflectance ratio values and then a combination of reflectance and ratio values were used to define the vector space. After the classifiers were developed, the training set data were tested against the classifier to see how well each worked against the data set used to develop it. The reflectance data (R, G, B) correctly classified 79% of the material types. The reflectance ratios (R/G, G/B, R/B) correctly classified 59%. When the reflectances and ratios were used to classify the material types, 90% were correctly classified.

* R, G and B are the red, green, and blue reflectances respectively.

Table 5.A-1 contains a breakdown on the classification accuracy for the materials described in Table 5.A-2. The results indicated that the photometric approach offered a tremendous power in classifying the materials studied to that point.

The data base for the photometric identification technique was expanded at that point in an attempt to increase the number of points used to develop the statistical classifiers for some of the more uncommon materials. Much of the error in the classification was due to the poorly defined probability density associated with small numbers of points for certain materials. In the expanded data set, 228 points were included in the dependent data set. Copper roofs were dropped from this group because there were too few points to generate a probability-density distribution. Glass was also eliminated since its use as a roofing material appeared to be quite uncommon. After the dependent data set was classified, the classifier was also applied to an independent data set consisting of 42 additional points. After classification for material type, the material classes were grouped based on emissivity values. For example, all asphalt roofs were grouped together because our emissivity results indicated they have the same emissivities within measurement errors. The groups were combined if the mean of the emissivities within a group was within 0.025 of the mean of the emissivities of another group. This combination is useful because a misclassification of a material into a group with the same emissivity does not result in an error in the final calculation.

The results of the analysis of the dependent and independent data are shown in Table 5.A-3. These results indicate that emissivity identification with a high degree of accuracy can be accomplished using the photometric approach. Eighty-six percent of the 42 additional material points were classified into a material type having an emissivity within 0.025 of that assigned to the actual material type. The major source of error was in misclassifying red clay tiles as red asphalt. If greater accuracy were required, additional parameters such as roof texture and a prior knowledge of roof pitch would certainly improve classification results. These inputs were not considered in the present demonstration study, but are available from the photographs used and could be included if more accurate classification were deemed necessary. Texture information, in particular, could be easily included in an automated classification system.

TABLE 5.A-1 MULTIVARIATE CLASSIFICATION ACCURACIES: PHOTOMETRIC TECHNIQUE
USING REFLECTANCES AND RATIOS COMBINED

PERCENT OF OBSERVATIONS CLASSIFIED AS:

ACTUAL CLASS	1	2	3	4	5	6	7	11	12	13	14	15	17
1	87.50	0	6.25	0	0	0	0	0	6.25	0	0	0	0
2	10.00	60.00	10.00	10.00	0	0	0	10.00	0	0	0	0	0
3	18.18	0	72.73	9.09	0	0	0	0	0	0	0	0	0
4	0	0	16.67	83.33	0	0	0	0	0	0	0	0	0
5	0	0	0	20.00	80.00	0	0	0	0	0	0	0	0
6	0	0	0	0	0	100.00	0	0	0	0	0	0	0
7	0	50.00	0	0	0	0	50.00	0	0	0	0	0	0
11	1.82	0	0	0	0	0	0	96.36	0	1.82	0	0	0
12	0	0	0	0	0	0	0	0	100.00	0	0	0	0
13	0	50.00	0	0	0	0	0	0	0	0	0	0	50.00
14	0	0	0	0	0	0	0	0	0	0	100.00	0	0
15	0	0	0	0	0	0	0	0	0	0	0	100.00	0
17	0	0	0	0	0	0	0	0	0	0	0	0	100.00

Total Sample Size = 140

Total Correct = 90%

TABLE 5.A-2 MATERIAL CLASSES FOR THE TRAINING SET DATA

Classification System

1. Asphalt - dark grey
2. Asphalt - light grey
3. Asphalt - dark green
4. Asphalt - light green
5. Asphalt - white
6. Asphalt - red
7. Asphalt - other

RESIDENTIAL

11. Tar with stones
12. Tar on felt
13. Slate
14. Clay tile
15. Painted Metal
17. Glass

COMMERCIAL

TABLE 5.A-3
RESULTS OF CLASSIFICATION OF MATERIAL
TYPES INTO EMISSIVITY GROUPS

	<u>Dependent Set</u>	<u>Independent Set</u>
Number of points	228	42
Percentage correctly classified	92	86

At this point, we would have liked to have calculated the error in emissivity resulting from classification of emissivity groups. Because there is still some doubt about the emissivities of certain roofs (especially, tar with stones), this could not be done in any detail. We would expect to do this analysis after several tar with stone type samples have been successfully run on the emissometer. At the present, it appears as though the error due to classification will be much smaller than the laboratory measurement error so that the statistical sum of the errors should be very close to the laboratory measurement error of 0.02.

5.B Biband Ratio Technique

A second technique for material identification was evaluated. This technique involved comparing signals from two infrared bandpasses. The potential advantage of this approach rested in the ability to collect all the data at night on a single collection flight.

5.B.1 Biband Ratio Approach

This approach used the ratio of the signal in two infrared bands to obtain information on the relative emissivities of the material in those bands.

The theoretical approach proceeded as follows:*

$$W_1 = K_1 T^n \quad (5.B-1)$$

where

W_1 is radiant energy

K_1 and n are calculated to minimize errors

T is temperature

The energy detected at aircraft altitude from a non-blackbody can be expressed as:

$$W_1 = \tau_1 \epsilon_1 K_1 T^n + W_{A1} \quad (5.B-2)$$

where

ϵ_1 is emissivity over the bandpass detected

W_A is radiant energy reaching the sensor independent of the source

τ_1 is the atmospheric transmission

T is temperature

* Note this approach is not as rigorous as that used in final calculations of temperature but should be sufficient for definition of relative emissivity values.

Using the approaches developed and demonstrated by Calspan (Schott 1977), it is possible to calculate the values of τ_1 and W_{A1} and how they vary with angle.

If we consider a second bandpass, the radiant energy from the same source can be expressed as:

$$W_2 = \tau_2 \epsilon_2 K_2 T^n + W_{A2} \quad (5.B-3)$$

expressing Equation 5.B-3 as

$$\frac{W_1 - W_{A1}}{\tau_1 K_1} = \epsilon_1 T^n \quad (5.B-4)$$

and dividing it into a similar expression for Equation 5.B-3 we obtain

$$\frac{\frac{W_2 - W_{A2}}{\tau_2 K_2}}{\frac{W_1 - W_{A1}}{\tau_1 K_1}} = \frac{\epsilon_2}{\epsilon_1} \quad (5.B-5)$$

where all the terms on the left-hand side are known.

Note that reflection terms used in the final calculation of temperature have been neglected in this treatment. Although this will introduce some error, Fiat (1966) and Lyon, et al. (1969), have indicated that meaningful information about relative emissivity values for material identification can be calculated with an even less rigorous treatment where atmospheric and background effects are completely neglected.

CLASSIFICATIONS:

RESIDENTIAL
 101 = DK GREY ASPHALT
 102 = LT GREY ASPHALT
 103 = DK GREEN ASPHALT
 104 = LT GREEN ASPHALT
 105 = WHITE ASPHALT
 106 = RED ASPHALT

COMMERCIAL
 211 = TAR AND STONES
 212 = FELT AND TAR
 213 = SLATE
 214 = RED CLAY TILE
 215 = PAINTED METAL
 217 = GLASS

FIGURE 5.B-1 RESULTS OF THE BIBAND RATIOING MATERIAL IDENTIFICATION ALGORITHM

5.B.2 Biband Results

The biband technique was evaluated by treating measured radiance values in the manner outlined above. The radiance values were obtained by densitometric analysis of 3-5 μ m on 8-14 μ m imagery of the Syracuse University area obtained during repetitive passes with different detectors (InSb filtered to 3-5 μ m and HgCdTe filtered to 8-14 μ m.) The results of this analysis for samples are shown in Figure 5.B-1. The high variability within the emissivity ratios for a given material compared to the variation in emissivities between ratios is obvious from this figure. This is just the opposite of what would be required for material identification. The variability in the ratio values obtained from a two-band spectral signature approach, therefore, appears to be unsuitable by itself as a material identification technique. It is possible that more numerous spectral bands and/or more carefully chosen bands in the emissive region of the electromagnetic spectrum (3-20 μ m) might be capable of isolating material signatures for roofing materials. Problems of decreased signal-to-noise for narrow bandpasses and high atmospheric absorption at most wavelengths will limit the probability of success in this direction. Because the photometric material identification technique had proven quite successful, we did not, and would not, recommend pursuing a long wavelength material identification technique.

5.C Photometric and Biband Results

The photometric and biband material identification approaches were combined to see if any improvement in the photometric techniques could be obtained by inputting the emissivity ratio as an additional component in the classification vector. In this case, the material vector would consist of the red, green, blue, red/blue, green/blue, and red/green reflectances as well as the emissivity ratio. These additional data were found to increase the classification accuracies of an independent data set by only 2%. The increased cost of the combined approach when weighed against the minimal increase in classification accuracy does not appear to warrant inclusion of the emissivity ratio component. We would, therefore, recommend use of the photometric material technique alone in any automated approach.

We should also point out at this time that other approaches to material identification exist. Daytime color imagery can, in most cases, be correctly interpreted for roofing material. It also seems reasonable to train owners to identify the roofing material, if not directly, then by association with a material display set up at a dissemination center. The final choice of a material identification technique will depend largely on the way the data are to be disseminated.

SECTION 6

AERIAL MEASUREMENT OF TEMPERATURE

The main thrust of this first phase effort was to identify, develop and perform a preliminary evaluation of a technique for aerial measurement of roof top temperatures. This section will review the procedures developed for temperature measurement (Section 6.A). The methods used in the error analysis will be presented (Section 6.B), and the expected results obtainable using the technology will be presented (Section 6.C).

6.A Procedures

The aerial measurement of temperature involves consideration of the expression for the radiant energy reaching an airborne sensor. We have expressed this energy (cf. Section 4) as

$$W(\theta) = \tau(\theta) \epsilon(\theta) W_T + W_A(\theta) + \tau(\theta) R(\theta) W_S \quad (6.A-1)$$

where $W(\theta)$ is the energy reaching the airborne sensor

$\tau(\theta)$ is the atmospheric transmission

$\epsilon(\theta)$ is the emissivity of the source

W_T is the radiant energy from the source associated with the surface temperature T

W_A is the energy from the air column that reaches the sensor

R is the reflectance of the source

W_S is the radiant energy from the sky incident on the source

θ is the view angle measured from the normal

All the variables are functions of the bandpass of the detector (generally 8-14 μ m) and we have dropped noting the dependence on altitude (h) for convenience. Figure 6.A-1 illustrates the energy paths expressed mathematically in Equation 6.A-2. Equation 6.A-1 holds for level, exposed roof surfaces. Roofs which are pitched or have adjacent structures rising above them will receive and reflect energy from background not entirely sky. The effect of background radiation can be included in Equation 6.A-1 by rewriting it as

FIGURE 6.A-1 ENERGY PATHS IN THE 8-14 μ m BAND-PASS
ACCORDING TO EQUATION 6.A-2

$$W = \tau \epsilon W_T + W_A + F\tau RW_S + (1 - F)\tau RW_B \quad (6.A-2)$$

(6.A-2)

$$W(\theta) = \tau(\theta) \epsilon(\theta) W_T + W_A(\theta) + F \tau(\theta) R(\theta) W_S + (1-F) \tau(\theta) R(\theta) W_b$$

where F is the fraction of the sky dome which is sky (cf. Figure 6.A-2)

W_b is the radiant energy from the background incident on the source
(8-14 μ m)

Rewriting Equation 6.A-2 as a function of the surface temperature term and omitting for convenience the functional dependence on θ , we obtain

$$W_T = [W - W_A - F\tau W_S - (1-F)\tau W_b] / \tau \epsilon \quad (6.A-3)$$

To measure surface temperature, therefore, we need to know all the terms on the right-hand side (RHS) of Equation 6.A-3.

Figure 6.A-3 is a flow chart depicting the steps necessary for determination of temperature. Several of the steps have already been discussed previously and will only be summarized here. The total radiant energy reaching the scanner (W) is determined through densitometric analysis of the film records combined with internal scanner calibration. This implies that a well calibrated quantitative scanner is used for data collection (cf. Section 2.B.1). The atmospheric effects including air radiance (W_A), sky irradiance (W_S) and atmospheric transmission (τ) are all obtained through use of the angular calibration technique (cf. Section 3.B). The angular calibration technique also allows calculation of the variation of τ and W_A with viewing angle. The value of W_S obtained from the angular calibration technique may not be sufficiently precise for some measurements. We have, therefore, developed an upward looking 8-14 μ m radiometer to better measure W_S and to more fully define the variation of W_S with angle. The work of Bell et al. (1960) indicates that the radiance from a clear sky, at any angle, can be calculated from the nadir value. This implies the total or fractional sky radiance required for the calculation of temperature could be obtained quite accurately from a single precise measurement with an upward-looking radiometer. Schott (1977) described how an upward looking radiometer could be included as part of the angular calibration technique to obtain extrapolated values for the incoming sky radiance on the ground using a wholly airborne system. Therefore, by combining the airborne measurement of W_S from a calibrated upward-looking radiometer, a more precise measurement

FIGURE 6.A-2 Illustration showing calculation of the fractional parts of the skydome which represent sky (F) and background (1-F). $F = (1 - \phi \cos (\frac{\pi}{2} - \phi)) / 2\pi$, where ϕ and ϕ are the angles subtended by the adjacent building width and height at point A in radians.

FIGURE 6.A-3 FLOW CHART FOR TEMPERATURE MEASUREMENT USING COMPREHENSIVE ANALYSIS INCLUDING THERMOGRAMS, COLOR PHOTOGRAPHS AND OWNER INTERACTION.

of W_s should be obtained. We would expect the precision to increase from the current value of about 5% to about 2 or 3% using this approach.

The next variable of interest on the RHS of Equation 6.A-3 is emissivity (ϵ). Emissivities (Reflectivities: $R = 1 - \epsilon$) are determined from look up tables of the normal spectral (8-14 μ m) values obtained in the laboratory or where appropriate, the spectral angular values (cf. Section 4.B). Recall that the angle of concern here which controls emissivity values is the angle between a perpendicular to the roof surface and the line of view in the plane defined by the sweep of the scanner. (This angle is not normally required as there is little change for ϵ for a large range of angles for most materials of interest.) Emissivity is a function of material type and it is therefore necessary to know the roofing material to use the look-up tables. The material can be identified in several ways as indicated in Figure 6.A-3. We would expect that some combination of owner interaction and photometric interpretation of daytime color photography would be the most probable approach (cf. Section 5.A). Tradeoffs in time, cost, user applications and owner knowledge of roofing materials need to be established. For example, if a survey is to be completely done before any owner interaction takes place, then the photometric technique, presumably in a highly automated form, would be exclusively used for material identification. If on the other hand, we can assume or develop an educated public who can tell us with confidence the material makeup of their roofs, then the photometric identification of materials may not be required at all or required for limited verification with a low degree of automation.

Referring to Figure 6.A-3, we see that at this point, we have sufficient information to calculate the rooftop temperature value if the roof is level and fully exposed to the sky.

In the case where the roof sees some background (cf. Figure 6.A-2), we need to account for the size of the background (1-F) and the radiant energy from the background (W_b) which will be reflected by the roof. The size of the background can be calculated from the distance to the nearest building (obtained from the thermal image) and the slope of the roof (estimated with the help of the owner). If a more rigorous calculation is necessary or desirable, daytime color imagery can be used to precisely define distances, slopes, etc. The background radiance

can be obtained from the recorded background radiance stored on the photographic record. The radiance from background objects observed at the sensor can be expressed as

$$W = \tau W_b + W_A \quad (6.A-4)$$

$$\text{where } W_b = \epsilon W_T' + F'R'W_s + R W_B' (1 - F') \quad (6.A-5)$$

W_T' is the radiant energy from the background due to its temperature

R' is the reflectance of the background object

F' is the fraction of the sky which background object sees

W_B' is the radiant energy from the background other than the sky reaching the background object

Conveniently, W_A and τ are known and Equation 6.A-4 can be solved directly for W_b . We do not need to know the values of the variables in Equation 6.A-5 which is provided only for completeness. As indicated in Figure 6.A-3, if we know W_b and F for a sloped roof, then the value of W_T , and therefore temperature, can be calculated.

The procedural approach we have discussed thus far has followed the flow chart presented in Figure 6.A-3. In Figures 6.A-4 and 6.A-5, we present two slightly different scenarios which could be followed. Figure 6.A-4 shows a flow chart which represents a procedural approach which could be followed using only nighttime thermal imagery. The procedural steps are the same as those discussed in considering the flow chart in Figure 6.A-3; however, in all cases, the owners input or measurements from the thermal imagery alone have been chosen as the procedure to be followed. This approach is attractive in that it eliminates the collection and analysis of the daytime data which would represent a considerable cost savings. It requires instead that the owner be prepared to answer some basic questions about his house. These would be questions about roofing material, roof style, house style and the relative height of neighboring houses. To help in obtaining data in this scenario, displays of roofing material and roof styles could be provided at an information dissemination center.

FIGURE 6.A-4 FLOW CHART FOR TEMPERATURE MEASUREMENT USING ONLY OWNER INTERACTION AND THERMAL IMAGERY

FIGURE 6.A-5 FLOW CHART FOR TEMPERATURE MEASUREMENT USING ONLY PHOTOGRAPHIC AND THERMAL IMAGERY

The owner would be asked to observe certain things about his house before coming to the dissemination center and then, by association with the displays, he or she could provide the required information. In many cases, (employing classical thermogram interpretation) the type of information required is already asked of home owners, but seldom constructively used. This "educated consumer" scenario needs to be evaluated in terms of how accurate the input (and therefore, the output) information would be. It offers the significant advantage of lower cost, potentially higher processing rates at dissemination centers and perhaps greater owner interest in the process.

We have presented a second alternative scenario described by the flow diagram in Figure 6.A-5. Once again all the procedures are included in the discussion of data flow associated with Figure 6.A-3. In this case, however, we have assumed no owner interaction or the "public as consumer". This might be the case if we were interested in conducting area-wide surveys, but only disseminating the data where they would be most useful; or if we wanted to present a fully finished result to the owner requiring no information from him (at least to obtain the temperature value or heat flow from his roof). This approach might be valuable where high throughput at dissemination centers was necessary because all data processing could be done in advance. The data on roofing material and background factors could all be obtained from the photometric or photogrammetric interpretation of the daytime color imagery. Final temperature (heat loss) maps could then be prepared for the user.

These scenarios of the "educated consumer" and the "public as consumer" are presented to demonstrate the range of potential utility of the technology developed for this effort. The integrated scenario represented by the flow chart of Figure 6.A-3 shows how these extremes could be used together if desired.

This section has demonstrated how the techniques presented in this report could be used to calculate rooftop temperatures. The definition and development of such a technique was the major objective of this program. Obviously, the next question is how well can we expect to measure temperature.

6.B Error Analysis

At this point we are interested in estimating how well we can expect to measure rooftop temperatures using aerial systems. Because of the numerous variables involved in the temperature measurement expression there is no unique simple answer. The degree to which we can measure temperature depends on the conditions under which the data are collected (i.e., the value of the variables) and on how well we can determine the value of the individual parameters involved in calculating the true surface temperature. To properly evaluate these errors, we first rewrite Equation 6.A-3 as

$$W_T = [W - W_A - F \tau (1 - \epsilon) W_s - (1 - F)(1 - \epsilon) \tau W_b] / \tau \epsilon \quad (6.B-1)$$

where $(1 - \epsilon)$ has been substituted for R .

We then need to calculate the error in W_T (hence, T) associated with each parameter. This is accomplished by taking the partial derivative of W_T with respect to each parameter (after Beers, 1953).

Thus, the error in W_T (s_{W_T}) associated with the combination of the error from each variable (e.g., s_ϵ) can be expressed as

$$s_{W_T} = \sqrt{\left(\frac{\partial W_T}{\partial \epsilon} s_\epsilon^2 + \frac{\partial W_T}{\partial \tau} s_\tau^2 + \dots \right)^{1/2}} \quad (6.B-2)$$

where

$$\frac{\partial W_T}{\partial \epsilon} = \left[\frac{W_A - W}{\tau \epsilon^2} + \frac{W_s F + W_b (1 - F)}{\epsilon^2} \right] \quad (6.B-3)$$

$$\frac{\partial W_T}{\partial \tau} = \frac{W_A - W}{\tau^2 \epsilon} \quad (6.B-4)$$

$$\frac{\partial W_T}{\partial W} = \frac{1}{\tau \epsilon} \quad (6.B-5)$$

$$\frac{\partial W_T}{\partial W_A} = - \frac{1}{\tau \epsilon} \quad (6.B-6)$$

$$\frac{\partial W_T}{\partial W_s} = \left(\frac{\epsilon - 1}{\epsilon} \right) F \quad (6.B-7)$$

$$\frac{\partial W_T}{\partial W_b} = \frac{(1 - F)(\epsilon - 1)}{\epsilon} \partial W_b \quad (6.B-8)$$

$$\frac{\partial W_T}{\partial F} = \frac{(1 - \epsilon)}{\epsilon} (W_B - W_S) \partial F \quad (6.B-9)$$

In terms of evaluating the magnitude of the individual errors, we refer back to the water temperature measurements discussed in Section 3. We know that the total error in measurement of water surface temperature can be conservatively estimated to be $\pm 0.71^\circ\text{C}$. Therefore, the expected error in the aerial measurement (S_{air}) can be expected to be of about the same magnitude since the error in the water temperature measurements taken at the surface were comparatively small.

The estimated distribution of the errors is shown in Table 6.B-1 for several actual data calibration sets used over water. Note in particular, that with the errors distributed as indicated, we consistently have an expected error slightly higher than the measured value of 0.65°C for water. (We have purposely been somewhat conservative throughout this analysis.) We should point out that the values of the variables and the associated errors used in Table 6.B-1 are appropriate for water temperature measurements. It is encouraging to note that, as indicated by the fall and winter data in Table 6.B-1, we would expect the measurement errors to decrease in the winter due to higher atmospheric transmission, less air radiance and lower sky temperatures.

6.C Results of the Error Analysis

In order to evaluate the expected errors in rooftop temperature, the value of each parameter and the expected error associated with it were evaluated for a set of conditions defined by an actual set of calibration data for heat loss mission. The first example in Table 6.C-1 shows the typical heat loss conditions with the errors associated with each variable the same as we had defined them previously for water. Atmospheric transmission is included as τ with a

TABLE 6.B-1

ERROR ANALYSIS FOR CALIBRATIONS OF ACTUAL WATER TEMPERATURES

EARLY SUMMER	EMNIS=	0.986	+/-	0.2	%
	TAU=	0.775	+/-	1	%
	T(APP)=	295	+/-	0.08	%
	W(AIR)=	2.99000E-03	+/-	1	%
	T(SKY)=	306	+/-	5	%
	DELTA EMM.=	0.017			
	DELTA TAU=	0.6585			
	DELTA T(APP.)=	0.301			
	DELTA W(AIR)=	0.152			
	DELTA T(SKY)=	0.236			
	TOTAL ERROR=	1.3645			
	•PROB.MAX.ERROR=	0.776731775			
	TRUE TEMP.=	297.9473757			
LATE SUMMER	EMNIS=	0.986	+/-	0.2	%
	TAU=	0.7794	+/-	1	%
	T(APP)=	295	+/-	0.08	%
	W(AIR)=	2.99000E-03	+/-	1	%
	T(SKY)=	295	+/-	5	%
	DELTA EMM.=	5.00000E-03			
	DELTA TAU=	0.6565			
	DELTA T(APP.)=	0.301			
	DELTA W(AIR)=	0.152			
	DELTA T(SKY)=	0.206			
	TOTAL ERROR=	1.3205			
	•PROB.MAX.ERROR=	0.766262520			
	TRUE TEMP.=	297.733749			
FALL	EMNIS=	0.986	+/-	0.2	%
	TAU=	0.902	+/-	1	%
	T(APP)=	295	+/-	0.08	%
	W(AIR)=	1.48000E-03	+/-	1	%
	T(SKY)=	241	+/-	5	%
	DELTA EMM.=	0.0825			
	DELTA TAU=	0.6435			
	DELTA T(APP.)=	0.263			
	DELTA W(AIR)=	0.066			
	DELTA T(SKY)=	0.0905			
	TOTAL ERROR=	1.1455			
	•PROB.MAX.ERROR=	0.708952572			
	TRUE TEMP.=	295.9607842			
WINTER	EMNIS=	0.986	+/-	0.2	%
	TAU=	0.85	+/-	1	%
	T(APP)=	280	+/-	0.08	%
	W(AIR)=	1.90000E-03	+/-	1	%
	T(SKY)=	240	+/-	5	%
	DELTA EMM.=	0.0635			
	DELTA TAU=	0.5815			
	DELTA T(APP.)=	0.2675			
	DELTA W(AIR)=	0.1035			
	DELTA T(SKY)=	0.1045			
	TOTAL ERROR=	1.1205			
	•PROB.MAX.ERROR=	0.659820620			
	TRUE TEMP.=	280.2861691			

precision of one percent. This is based on the results of replicate calibrations of the same scene by different personnel. The atmospheric radiance term $W(\text{AIR})$ is obtained by the same calibration equations and has an expected precision of 2% as indicated in Table 6.C-1. The expected error in our knowledge of atmospheric transmission and air radiance result in independently calculated errors of 0.61°C^* and 0.23°C as indicated. The error in apparent temperature is simply internal scanner calibration accuracy which at 0.08% converts to about 0.28°C . The imprecise knowledge of sky background temperature introduces the largest single source of error in this particular analysis. The wholly airborne calibration technique yields values of T_{sky} that can only be expected to be within about 5% or $\pm 12^{\circ}\text{C}$ of the true value. The change in this table compared to the case for water is the emissivity error which we feel should be much closer to 2% for roof surfaces as indicated in Section 4. This introduces a fairly significant error of about 0.44°C . We have also added the effects of background radiation (W_b and F) which are not present for water. Our estimates of the error in W_b and F are based on measuring W_b by densitometric analysis of the thermogram and estimating F by visual interpretation of daytime imagery or by user interaction. Both of these terms introduce only small errors in the measurement of actual temperature. We have at this point allowed for some error in F . Under certain conditions (e.g., warmer background), we might want to attempt to decrease the error in F to improve the overall measurement of T . However, it appears that for most conditions, the error in T_s is reasonably insensitive to fairly sizeable changes in F . This makes it easy on the interpreter or owner who can roughly estimate F from simple look-up tables such as those found in Appendix A. When we combine the individual error terms we arrive at a final expected error of about 1.01°C for these conditions. Note that in this analysis, we have assumed all of the error terms to be independent although we know, for instance, that errors in τ and W_A are somewhat compensating and will, therefore, tend to reduce slightly the total expected error.

* Note that the calculated errors presented in this discussion are the average of the three examples in Figure 6.C-1.

TABLE 6.C-1

THREE EXAMPLES OF ERROR ANALYSIS SHOWING THE
EFFECT OF DIFFERENT DEGREES OF PRECISION FOR CERTAIN PARAMETERS

EXAMPLE 1

EMMIS=	0.9	+/-	2	%
TAU=	0.88	+/-	1	%
T(APP)=	278	+/-	0.08	%
W(AIR)=	1.90000E-03	+/-	2	%
T(SKY)=	240	+/-	5	%
T(B)=	280	+/-	0.3	%
FRACTION=	0.8	+/-	10	%
DELTA EMM.=	0.4785			
DELTA TAU=	0.6065			
DELTA T(APP.)=	0.284			
DELTA W(AIR)=	0.2275			
DELTA T(SKY)=	0.6775			
DELTA F=	2.50000E-03			
DELTA T(B)=	0.0195			
EXPECTED ERROR=	1.09023369			
TRUE TEMP.=	277.9420504			

EXAMPLE 2

EMMIS=	0.9	+/-	1.7	%
TAU=	0.88	+/-	1	%
T(APP)=	278	+/-	0.08	%
W(AIR)=	1.90000E-03	+/-	2	%
T(SKY)=	240	+/-	5	%
T(B)=	280	+/-	0.3	%
FRACTION=	0.8	+/-	10	%
DELTA EMM.=	0.4065			
DELTA TAU=	0.6065			
DELTA T(APP.)=	0.284			
DELTA W(AIR)=	0.2275			
DELTA T(SKY)=	0.6775			
DELTA F=	2.50000E-03			
DELTA T(B)=	0.0195			
EXPECTED ERROR=	1.06060808			
TRUE TEMP.=	277.9420504			

EXAMPLE 3

EMMIS=	0.9	+/-	1.7	%
TAU=	0.85	+/-	1	%
T(APP)=	278	+/-	0.08	%
W(AIR)=	1.90000E-03	+/-	2	%
T(SKY)=	240	+/-	2	%
T(B)=	280	+/-	0.3	%
FRACTION=	0.8	+/-	10	%
DELTA EMM.=	0.433			
DELTA TAU=	0.614			
DELTA T(APP.)=	0.2865			
DELTA W(AIR)=	0.23			
DELTA T(SKY)=	0.2645			
DELTA F=	2.00000E-03			
DELTA T(B)=	0.019			
EXPECTED ERROR=	0.877378197			
TRUE TEMP.=	280.0574955			

The value of the approach can be seen by considering Examples 2 and 3. In example 2, we see the decrease in total error associated with a decreased error in the estimate of emissivity. At least for these conditions, small decreases in the error in ϵ do not appear to gain very much. In terms of improving the total expected error, we must weigh all the contributions to see where the most is gained with the least investment of time and money. Example 3 shows one improvement which we feel can be fairly readily accomplished. This shows the decrease in total error associated with a decreased error in the measurement of W_{sky} . We feel that use of an upward-looking 8-14 μ m radiometer could easily and relatively inexpensively provide considerable improvement in our ability to measure rooftop temperature. This analysis also indicates that imprecision in the measurement of atmospheric transmission is also a major factor in the total error analysis. We have, therefore, initiated efforts directed at improving the precision of the atmospheric calibration technique.

While the values illustrated in Table 6.C-1 are typical of certain flight conditions, they are not universal. The actual expected error will vary somewhat with a change in the value of the error associated with any of the input variables shown. Care must therefore be taken in evaluating the flight conditions, instrumentation errors and types of targets surveyed before final estimates on the total measurement error can be made.

The analysis presented in this section can also be useful in illustrating the limits of classical analysis techniques. In Table 6.C-2, two examples of typical rooftop analysis are shown. These two roofs have all the same collection conditions and errors associated with them. The only differences are in the emissivities associated with roofing material and in the F factor associated with adjacent structures or roof pitch. Note that neither the emissivities nor the F factors chosen for this illustration are at all unlikely. What we want to stress is that the apparent temperatures expressed as a gray tone on the thermogram would be identical for these two structures. Yet their actual temperatures differ by nearly 4°C. Real, but undetected differences of this type, or false differences, often occur on thermal images. The present techniques of classical image interpretation do not begin to detect these effects. Indeed, the limits of the human eye in detecting subtle differences compound the problem. Thus, we are convinced that the quantitative approach

TABLE 6.C-2

EXAMPLE OF TWO ROOFS WITH IDENTICAL APPARENT TEMPERATURES ON
A THERMOGRAM BUT WITH MARKEDLY DIFFERENT ACTUAL TEMPERATURES

EXAMPLE 1

EMMIS=	0.95	+/-	1.7	%
TAU=	0.88	+/-	1	%
T(APP)=	278	+/-	0.08	%
W(AIR)=	1.90000E-03	+/-	2	%
T(SKY)=	240	+/-	5	%
T(B)=	284	+/-	0.3	%
FRACTION=	0.7	+/-	10	%

DELTA EMM.=	0.3075
DELTA TAU=	0.5825
DELTA T(APP.)=	0.2715
DELTA W(AIR)=	0.2175
DELTA T(SKY)=	0.284
DELTA F=	1.00000E-03
DELTA T(B)=	0.015
EXPECTED ERROR=	0.797347478
TRUE TEMP.=	276.4315625

EXAMPLE 2

EMMIS=	0.85	+/-	1.7	%
TAU=	0.88	+/-	1	%
T(APP)=	278	+/-	0.08	%
W(AIR)=	1.90000E-03	+/-	2	%
T(SKY)=	240	+/-	5	%
T(B)=	284	+/-	0.3	%
FRACTION=	1	+/-	10	%

DELTA EMM.=	0.543
DELTA TAU=	0.6235
DELTA T(APP.)=	0.291
DELTA W(AIR)=	0.233
DELTA T(SKY)=	1.311
DELTA F=	6.50000E-03
DELTA T(B)=	0
EXPECTED ERROR=	1.59415636
TRUE TEMP.=	280.4556569

suggested here is necessary if serious attempts at objectively interpreting thermograms for heat loss are to be considered.

The implications of precise temperature measurement for heat loss determination are discussed in the next section.

SECTION 7

HEAT LOSS MEASUREMENTS

Aerial measurements of heat loss involve two major steps. The first is developing procedures for aerial measurements of rooftop temperature. The second is defining procedures for relating rooftop temperature values to building heat loss.

7.A Relationship Between Heat Loss and Temperature

Knowing that aerial thermograms tell us something about surface temperatures, we will attempt to express rooftop heat loss as a function of surface temperature.

For the purposes of this report, we will assume that we are observing a quasi-steady state conditions with heat flow outward from the roof surface. For the present, we will also assume a flat roof with no attic ventilation. The heat flow can then be expressed as

$$q = q_c + q_r = h_c (T_s - T_a) + \epsilon \sigma T_s^4 - \epsilon W_s \quad (7.A-1)$$

where q is net heat flow

$q_c = h_c (T_s - T_a)$ is the component due to convection with
 $T_s - T_a$ as the driving factor

$q_r = \epsilon \sigma T_s^4 - \epsilon W_s$ is the component due to radiation

h_c is the convective heat transfer coefficient and is a function of wind speed, surface roughness and length of surface (cf. Cole and Sturrock 1977).

T_s is the surface temperature

T_a is the ambient air temperature at roof level

ϵ is the total surface emissivity

σ is the Stefan-Boltzmann constant

W_s is the total radiant energy from the sky incident on the surface (absorptivity equals emissivity).

For a sloping roof or one that "sees" a background other than the sky, we can write Equation 7.A-1 (after Goldstein 1978) as

$$q = h_c (T_s - T_a) + F(\epsilon \sigma T_s^4 - \epsilon W_s) + (1-F) (\epsilon \sigma T_s^4 - \epsilon W_b) \quad (7.A-2)$$

where F is the fraction of the "skydome" which is sky

$(1-F)$ is the fraction of the "skydome" which is background other than the sky.

W_b is the radiant energy from the background incident on the surface.

We have at this point introduced a number of unknowns; T_s , ϵ , W_s , F and W_b . T_a can be determined from local meteorological data. A number of means for estimating h_c are available, though most of them require some knowledge of wind speed and surface material (cf. Cole and Sturrock 1977). Figure 7.A-1 is an illustration of the energy paths described by Equation 7.A-2.

The heat flow, q , of Equation 7.A-2 can also be related to the thermal resistance or R-factor of the roof structure since

$$q = \frac{1}{R} (T_i - T_s) \quad (7.A-3)$$

where T_i is the interior air temperature below the roof. Estimates of R-values based on q may be reasonably valuable for unventilated structures where T interior is known if T_s can be accurately determined from aerial thermograms. We should recall in all cases, however, that what we are really interested in is the heat loss value of q . This represents the energy and money we wish to conserve.

The effects of attic ventilation can also be included in Equation 7.A-2 after the method of Brown (1978a). This yields

Figure 7.A-1: ENERGY EXCHANGE AT A ROOF SURFACE ACCORDING TO EQUATION 7.A-2

$$q = h_c(T_s - T_a) + F(\epsilon\sigma T_s^4 - \epsilon W_s) + (1-F)(\epsilon\sigma T_s^4 - \epsilon W_b) \quad (7.A-2)$$

$$q = q_c + q_r + q_v = h_c(T_s - T_a) + F(\epsilon \sigma T_s^4 - \epsilon W_s) + (1 - F)(\epsilon \sigma T_s^4 - \epsilon W_b) + C_p V n (T_{att} - T_a) \quad (7.A-4)$$

where C_p = heat capacity of air

n = number of air exchanges per hour in attic

T_{att} = average attic air temperature

Brown et al (1978) indicates considerable success in estimating ventilation rates by classical interpretation of aerial photographs. Most of the remaining discussion applies to ventilated as well as non-ventilated structures; however, the ventilation component has been neglected for simplicity. We do not mean to imply by this that ventilation is a trivial component. It does not, however, necessarily represent a component of heat loss through the roof itself and this is the main thrust of the current effort. We plan to include ventilation effects in our future efforts to objectify the estimates of total heat loss upward through the ceiling of residential structures.

7.B Approach to Heat Loss Measurement

The question that faces us at this point is can we determine the values of the parameters in the heat loss equation (Equation 7.A-2) and how well can we determine them relative to our need to know heat loss. For example, if our goal is to objectify heat loss and place a structure in a category of say 1 to 5, we would want the cumulative probable error in knowing heat loss to be less than about 10% of the maximum expected heat loss value to permit designated heat loss categories. The program reported on here has principally addressed quantitative measurement of temperature. With the identification of procedures for quantitative measurement of temperature, we feel it is appropriate at this point to take a more serious look at the heat loss question.

Referring to Equation 7.A-2, we believe we can measure T_s which is the dominant term to about 1°C or better based on the discussion in Section 6.C. Procedures for identifying the other variables are discussed here, but in most cases the accuracy and precision of the measurement techniques are not defined.

The total sky radiance, W_s , can potentially be defined by any of three approaches. The simplest approach would be to utilize $W_{s\lambda}$ and calculate the total energy that would be associated with W_s . This, however, requires an optically "gray" sky which means that emissivity for the sky is not a function of wavelength or that the emissivity of the sky has a very well-defined functional relationship with wavelength. This possibility should be investigated further. The second approach involves direct measurement of W_s . This would be accomplished by mounting an upward-looking broadband radiometer (Thermopile) in the collection aircraft. The profile calibration procedure described by Schott (1977) would permit extrapolation of the W_s value observed at flight altitude to the value incident on the ground. Calculating W_s using an additional sensor, though untested, is reasonably well assured of success, though obviously more involved than the first approach suggested. A third approach would involve use of existent models relating sky radiance to such factors as ambient air temperature and relative humidity, etc.

The fraction of the "skydome" which is sky, F , can be estimated by an interpreter viewing an image of the surface (roof top) and its surroundings. A daytime stereo image pair would be particularly valuable for this. A detailed knowledge of F should only become important when F is considerably less than 1 and when the difference between background and total sky temperature is large. For most structures, F should be close to one and background effects will be small. Thus, the precision needed for the heat loss calculations should probably be about the same as for the temperature calculations.

A number of procedures are potentially available for identification of material type including classical interpretation of daytime color imagery or photometric interpretation of daytime color imagery. Knowledge of material type would be used to find ϵ , and h_c^* from look-up tables. W_b would be determined through calculation of the background temperature from the thermogram imagery and conversion of the temperature to radiant power. Depending on the results of more detailed error analysis, the spectral and broadband emissivities of the background might be required. If so, they could be obtained in the same manner as the target emissivities.

* Wind speed would also be required to obtain h_c .

7.C Heat Loss Error Analysis

A detailed error analysis of the heat loss equations such as that undertaken for the roof temperature calculations was beyond the scope of this effort. A limited effort was undertaken to begin to evaluate the limits of the error required for temperature measurement. Once again, the exact values will vary depending on the values and expected errors associated with each parameter.

We evaluated one case which we expected to be toward the worst-case extreme for heat loss measurements. In this case, the air temperature was about 40° with 4 mph winds and clear skies. This should represent a low contrast condition between structures. It is, however, well within all the currently accepted standards for data collection. For simplicity, the unventilated case was used for these calculations and the broadband emissivity of the roof was taken to be equal to the 8-14 μ m emissivity. The results of applying the heat loss equations under these conditions are shown for a narrow range of values in Table 7.C-1.a. In this illustration, we have again kept the apparent temperature constant (i.e., all these structures will appear identical on a thermogram) and varied the F values and the emissivity values slightly. In viewing this table, recall that the F values will commonly vary from about 0.65 to 1.0 and emissivities will vary from 0.82 to 0.97. Note that at this point we have succumbed to the trend toward calculating R-values. This is intended to provide the reader with a common reference while we continue to stress the greater importance of the heat loss value q. We have defined, for this data set, a ranking system to illustrate the type of information we would eventually like to have available to users. Because both roof temperature and heat flow are extremely dependent on the conditions under which the data are collected, they are meaningless to the average individual. A ranking system, indicating to the owner of a building how much heat he is losing compared to some optimum value, can convey a great deal more information.

In considering the data in Table 7.C-1.a, it appears obvious that under these conditions we would want to know roof temperatures to better than 1°C and perhaps to 0.5°C. With the currently expected capabilities of somewhat less than 1°C, we appear to be within reasonable reach of obtaining objective heat loss values. Some improvements in how well we can measure roof temperature

or alternate specifications on when to collect data (i.e., colder air temperature) to optimize roof temperature differences may be required. Table 7.C-1.b contains an example of the effects of colder ambient conditions on heat flow. Here again the apparent temperatures of all the structures is the same (-5.5°C). Only in low heat flow (high R value) cases would we expect to have serious problems if a calibration accuracy of better than 1°C were obtained. The necessity for such requirements and the exact limits to be set await a more detailed analysis of the heat flow calculations and a final testing of how well temperatures can be measured.

One serious question of concern is raised in considering the information contained in Table 7.C-1. We have displayed here a fairly sizeable variation in heat loss which would go undetected by classical techniques. In addition, in Section 6, we indicated that temperature differences as high as 4°C could go undetected by classical interpretation techniques. In Table 7.C-1, we are displaying a range of heat loss values associated with an even smaller temperature range than this. These results, while preliminary, indicate that comparison of heat loss between structures using classical techniques should be done, if at all, with the utmost care to ensure nearly total similarity between the structures. Care should also be taken in interpreting changes or lack of changes within a structure to ensure that view factors or emissivity effects are properly interpreted.

TABLE 7.C-1.a

RESULTS OF APPLYING THE HEAT LOSS MODEL IN THE
CASE OF A FIXED APPARENT TEMPERATURE

APPARENT ROOF TEMP = 5 DEG C

CONDITIONS:

TAU = 0.88
 W(AIR) = 1.90E-03
 TSKY(8-14) = 240 DEG K
 T(BACKGROUND) = 7 DEG C
 WINDSPEED = 4 MPH
 T(AMBIENT AIR) = 7 DEG C
 T(INSIDE) = 21 DEG C
 TSKY(BROADBAND) = 260 DEG K

SKYDOME FRACTION	EMISSIONITY	ROOF TEMP (DEG C)	Q (WATTS/M ²)	R (HR-FT ² /BTU)	RANKING*
0.7	0.90	5.13	23.41	3.85	2
0.7	0.92	4.57	14.82	6.29	3
0.7	0.93	4.29	10.62	8.93	3
0.7	0.94	4.02	6.50	14.81	4
0.8	0.90	5.31	34.34	2.59	1
0.8	0.91	5.01	29.86	3.04	2
0.8	0.92	4.71	25.34	3.65	2
0.8	0.93	4.42	20.91	4.50	2
0.8	0.94	4.13	16.56	5.78	3
0.8	0.95	3.85	12.29	7.92	3

* 1. Q>30 2. 20<Q<30 3. 10<Q<20 4. 0<Q<10

TABLE 7.C-1.b

RESULTS OF APPLYING THE HEAT LOSS MODEL IN THE
CASE OF A FIXED APPARENT TEMPERATURE

APPARENT ROOF TEMP = -5.5 DEG C

CONDITIONS:

TAU = 0.88
 W(AIR) = 1.90E-03
 TSKY(8-14) = 230 DEG K
 T(BACKGROUND) = -3 DEG C
 WINDSPEED = 4 MPH
 T(AMBIENT AIR) = -7 DEG C
 T(INSIDE) = 20 DEG C
 TSKY(BROADBAND) = 250 DEG K

SKYDOME F	EMISSIVITY	ROOF TEMP(DEG C)	Q(WATTS/M ²)	R (HR-FT ² /BTU)	RANKING*

0.7	0.84	-6.81	35.32	4.31	2
0.7	0.86	-7.25	28.92	5.35	3
0.7	0.88	-7.68	22.70	6.92	3
0.7	0.90	-8.09	16.74	9.52	3
0.7	0.92	-8.47	11.00	14.69	1
0.7	0.94	-8.85	5.49	29.83	1
0.8	0.84	-6.20	51.99	2.86	1
0.8	0.86	-6.72	44.44	3.41	2
0.8	0.88	-7.23	37.09	4.17	2
0.8	0.90	-7.72	29.95	5.25	3
0.8	0.92	-8.19	23.08	6.93	3
0.8	0.94	-8.64	16.49	9.86	3

* 1. Q>48 2. 48>Q>32 3. 32>Q>14 4. 14>Q>0

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

The objective of the first phase of this research was to identify a technique suitable for use in measuring rooftop temperatures. The main tasks required to accomplish this goal included accounting for atmospheric and background effects on thermograms, measurement of emissivities of common building materials and definition of techniques suitable for associating emissivity values with roof type. In addition, an error analysis was to be performed to aid in evaluating the potential utility of the technique identified. Each task has been accomplished and a technique incorporating several viable options for its actual application has been identified.

Procedures for measurement of atmospheric and background effects have been identified and most of them have been demonstrated. A technique for measurement of the emissivity of roofing material was developed and demonstrated. Thirty-three different roofing materials were measured as part of this effort. Several alternate approaches for material identification were developed and initially demonstrated. It appears based on these results that the final choice in identifying a technique for material type will depend on the users' need. For example, if limited user interaction is required, the photometric techniques appear most suitable. If more extensive user interaction is possible, then a questionnaire, coupled with an educational display at a dissemination center, may be the best approach. Actually, several alternatives are available which could be keyed to the particular requirements of each survey.

The error analysis performed as part of this effort indicates that we can expect to measure rooftop temperatures to within about 1°C of the true value. The error values are, however, dependent on collection conditions and as a result, should be expected to vary somewhat. Procedures for improving measurement techniques to reduce the error further have been suggested. In conducting the error analysis, a limited comparison to the current SOA procedure for interpretation of thermograms was conducted. It appears likely that errors in classical interpretation are most likely based on the failure of present approaches to account for several significant variables. The current limits

to interpretation are lessened if only variations within a single roof are considered. In addition, if only flat roofs, and particularly flat roofs made of one material, are considered, the potential for correct interpretation of temperature variations (though not true temperature) should improve considerably.

Based on the success of the first phase efforts and the limitations of the present state-of-the-art, we recommend that a test of the techniques identified be conducted to more fully assess the capabilities and limitations of the approach. We would also recommend that efforts be initiated to evaluate the potentials for applying the rooftop temperature measurement technique to the objective assessment of building heat loss. The initial steps necessary to evaluate this approach were discussed in Section 7.

For the purpose of summary and as a means of demonstrating the utility of the techniques developed during this program, let us once again view the images presented in the frontispiece. First, we will attempt to interpret the thermogram assuming that the only methods available are the classical techniques which state that the brighter an object appears, the warmer it actually is. Let us use this approach in evaluating two particular buildings, the rectangular, "three-piece" building near the stadium wall, and the square red-roofed building directly to its left. The square building appears to have several brightness levels which would indicate correspondingly different temperature values. By using classical techniques, we would assume that the red portions of the roof are much cooler than the grey or whitish sections which appear quite warm. Likewise, we would say that the southern-most end of the rectangular building is much warmer than the opposite end or the middle of the building. Although these observations indeed may be true, it is difficult to place a great deal of confidence in them without knowing something about the actual roofing material and its ability to radiate heat (i.e., its emissivity), the meteorological conditions and other variables. Consequently, this significantly limits the application of the classical state-of-the-art techniques used in thermogram interpretation.

Now let us apply, to the same situation, information such as that developed during this program on the emissivities of various roofing materials. By properly identifying the red roofing material as clay tile, the grey material

on the square roof as built-up stone, and the grey materials on the rectangular building as asphalt in the center and built-up stone on the ends, we can now reevaluate and confirm, where possible, some of the earlier temperature observations. First, the emissivity of red clay tile has been determined to be lower than that of either built-up stone or asphalt. Consequently, a roof made of clay tile will generally appear cooler than a stone (or asphalt) roof even if they are both losing the same amount of heat. Secondly, it is also possible to make a more definitive comparison of the roof surfaces of the rectangular building. Asphalt and built-up stone have approximately the same emissivity; hence, one can say with some degree of confidence that the brighter roof surface is indeed warmer than either the opposite end or the middle roof surface. (In fact, the asphalt roof was only recently installed and the cool appearance may be due, in part, to the performance of the insulation.)

To this point, we have described only qualitative approaches to evaluating heat loss levels from a thermogram. However, many users of thermography are also interested in the quantification of these levels. As a result of the theoretical work developed on this program, it is now possible to discuss the quantitative measurement of roof surface temperature and roof-top heat loss. To demonstrate how these new interpretation techniques would be used, we will apply them to the roof surfaces in our example. By assuming that the brighter surfaces are warmer and by assigning an apparent temperature value to each brightness level (classical approach), it is possible to arrive at an apparent temperature value for any given roof surface. If we do this for the red clay tile roof and the built-up stone on the roof of the square building (i.e., the grey material surrounding the center peak), we find that the stone roof appears to be about 3.8°C warmer than the red clay tile. However, if we take into account such variables as the emissivity value, the atmospheric conditions, the radiation from the sky and the radiation from the background, we now find that the actual difference between the roof temperatures is only 1.7°C - only half of what was previously observed. If we proceed to determine the heat loss values for these roofs, we find that the difference in heat loss levels for the uncorrected temperature values is about 2.5 times as great as that of the corrected values. Thus, we would have erroneously assumed that the warm surface was losing more

heat (and the cool surface, less) than it actually is. It is this type of observation which the interpretation techniques discussed in this report will enable us to avoid.

SECTION 9

REFERENCES

- Beers, Y. 1953, "Introduction to the Theory of Errors," Addison - Wesley Publishing Co., Cambridge, Massachusetts
- Bell, E.F., L. Eisner, J. Young, and R.A. Oetjen. 1960, "Spectral Radiance of Sky and Terrain at Wavelengths Between 1 and 20 Microns II. Sky Measurements," Journal of the Optical Society of America, Vol. 50 (12) pp. 1313-1320
- Bowman, R.L. and J.R. Jack. 1977, "Application of Remote Thermal Scanning to the NASA Energy Conservation Program, "NASA-TM-X-73570, 24 p., Lewis Research Center, Cleveland, Ohio
- Brown, R.J. and B.G. Young. 1975, "Spectral Emission Signatures of Ambient Temperature Objects," Applied Optics, Vol. 14 (12) pp. 2927-2934.
- Brown, R.J. 1978, "Infrared Scanner Technology Applied to Building Heat Loss Determination," Canadian Journal of Remote Sensing, Vol. 4 (1).
- Brown, R.J. 1978, "Canadian Experience with the Use of Aerial Thermography," Proceedings Thermosense I, Chattanooga, Tennessee, September, 1978.
- Brown, R.J., P.M. Teillet and J. Cihlar. 1978, "The Effects of Attic Ventilation on Residential Heat Loss Analysis," Canadian Centre for Remote Sensing, Ottawa, Canada.
- Buettner, K.J.K. and C.D. Kern. 1965, "The Determination of Infrared Emissivities of Terrestrial Surfaces," Journal of Geophysical Research, Vol. 70 (6) pp. 1329-1336.
- Burch, D.M., T. Kusuda and D.G. Blum. 1977, "An Infrared Technique for Heat Loss Measurement," NBS-TN-933, 55p., National Bureau of Standards, Washington, D.C.
- Cengas Surveys Energy Waste in Buildings," 1975, News Feature: AGA Monthly, Vol. 57 (10) pp. 4-6.
- Cihlar, J. 1976, "Thermal Infrared Remote Sensing: A Bibliography," Canadian Center for Remote Sensing, Research Report 76-1, 46 p.
- Cihlar, J., R.J. Brown, G. Lawrence, J.N. Barry. R.B. James. 1977, "Use of Aerial Thermography in Canadian Energy Conservation Programs," Proceedings of 11th International Symposium on Remote Sensing of the Environment, Ann Arbor, Michigan, April, 1977
- Cole, R.J. and N.S. Sturrock. 1977, "The Convective Heat Exchange at the External Surface of Buildings," Building and Environment, Vol. 12, pp. 207-214, Pergamin Press

- Dick, J.M. and F.A. Schmer, eds. 1978, "Aerial Infrared Users' Manual, " Report HCP/M4161/D, Prepared for U.S. Department of Energy, Washington, D.C.
- Evans, J.B. "Airborne Thermography-Flight Plan for Tomorrow." Proceeding ASP; Thermosense I, Chattanooga, Tennessee, Sept. 1978.
- Fiat, G. 1966, "Geophysical Survey Method Comprising Detection Infrared in Two Wavelength Bands," U.S. Patent 3,278,746.
- Goldstein, R.J. 1978, "Application of Aerial Infrared Thermography to the Measurement of Building Heat Loss," ASHRAE Transactions 1978, Vol. 84, Part 1.
- Gubareff, G.G. et al. 1960, "Thermal Radiation Properties Survey: A Review of the Literature," 2nd Ed. Honeywell Research Center, Minneapolis-Honeywell Regulator Company, Minneapolis, Minnesota
- Holter, M.R. et al. 1962, Fundamentals of Infrared Technology, MacMillen Company, New York.
- Hudson, R. 1969, Infrared Systems Engineering, John Wiley and Sons, New York.
- Hurley, C.W. and K.G. Kreider. 1976, "Applications of Thermography for Energy Conservation in Industry," Report No. NBS TN-923, National Bureau of Standards, Department of Commerce, Washington, D.C. 34p.
- Jack, J.R. 1978, "Aerial Thermography for Energy Conservation," NASA-TM-78959, 22p., 22 p., Lewis Research Center, Cleveland, Ohio.
- Lorenz, D. 1968, "Temperature Measurements of Natural Surfaces Using Infrared Radiometers," Applied Optics, 1968.
- Lyon, R.J.P. and J.W. Patterson. 1969, "Airborne Geological Mapping Using Infrared Emission Spectra," Proceedings of the 6th Symposium on Remote Sensing of Environment, University of Michigan, Ann Arbor: 527-552.
- Morrison, D.F. 1967, "Multivariate Statistical Methods," McGraw Hill, New York.
- Munish, R.H. and S.J. Marshall. 1977, "Infrared Thermography of Buildings: Qualitative Analysis of Window Infiltration Loss, Federal Office Building, Burlington, Vermont," CRREL-SR-77-29, 22 p., U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.
- Paljak, I. and B. Pettersson. 1972, "Thermography of Buildings, "Svensk Byggtjarst, Box 1403, S-11184 Stockholm Sweden, 56 p.
- Piech, K. R. and J.R. Schott. 1974, "Atmospheric Correction for Satellite Water Quality Studies," Proceedings of the SPIE, Vol. 51, pp. 84-89.

- Piech, K.R. et al. 1974, "Method for Extracting Photometric Information from Aerial Photographic Imagery," U.S. Patent 3,849,006, November 19, 1974.
- Pivovonsky, M. and M.R. Nagel. 1961, "Tables of Blackbody Radiation Functions," MacMillen Company, New York.
- Schott, J.R. and T.W. Gallagher. 1976, "Profile Technique for Calibration of Infrared Thermal Imaging Systems," U.S. Patent 3,970,848, July 20, 1976.
- Schott, J.R. 1977, "Thermal Remote Sensing Calibration Techniques," Calspan Report No. NA-6019-M-1, NTIS No. PB-269471.
- Schott, J.R. 1978, "Principles of Heat Loss Determination Using Infrared Thermographic Techniques," Proceedings Thermosense I, Chattanooga, Tennessee, September 1978.
- Schott, J.R. 1978, "Principles of Thermal Infrared Remote Sensing for Heat Loss Determination," Proceedings of the ASP, Albuquerque, New Mexico, October, 1978.
- Schott, J.R. 1979, "Temperature Measurement of Cooling Water Discharged from Power Plants," Photogrammetric Engineering and Remote Sensing, Vol. 45 (6) pp. 753-761.
- Shumaker et al. 1979, "Status of Thermal Imaging Technology as Applied to Conservation," Report No. HCP/M 4228-01, Prepared for U.S. Department of Energy, Washington, D.C. 109p.
- Tanis, F.J., R.E. Sampson and T.W. Wagner. 1976, "Thermal Imagery for the Evaluation of Construction and Insulation Conditions of Small Buildings," Final Report No. 116600-12-F Environmental Research Institute of Michigan, Ann Arbor, Michigan.
- Tobaisson, W. and C. Korhonen. 1978, "Summary of Corps of Engineers Research on Roof Moisture Detection and the Thermal Resistance of Wet Insulation," CRREL-SR-77-29, 8 p., U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.
- Van der Berg, A.J. 1976, "Infrared is Not a Panacea - Use Discretion," SPIE Vol. 78: Low Light Level Devices, pp. 41-43.
- Wolfe, W.L. 1965, "Handbook of Military Infrared Technology," U.S. Government Printing Office.
- Wormser Scientific Corporation 1976, "Report of Infrared Water Temperature Measurements of the Hudson River Made September 24, 1976. Wormser Scientific Corp. Report, Stamford, Connecticut.

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX A

GEOMETRIC SCENARIO FOR ESTIMATING
SKYDOME AND BACKGROUND FRACTIONS

May 23, 1979

TO: J. R. Schott
FROM: C. B. Kirby
SUBJECT: 1-F Calculations

In order to estimate the influence of the emitted energy of the background in the temperature of a roof, a geometric scenario was devised to estimate F and 1-F. The following assumptions were made:

- 1] By estimating the fraction of skydome (F) and fraction of background (1-F) that a particle of the roof at the mid-point sees, this will be sufficient as an estimated integration over the entire roof.
- 2] The peak of the roof is the middle of the house.
- 3] The width of the house and the peak-to-peak distance to the neighboring house can be obtained from the thermal and/or photographic imagery.

The widths of the houses were taken to be 20, 24, 28, 32, 40 and 50 feet. The slopes of the roofs were taken to be 0, 15, 30 and 45 degrees. In varying the peak-to-peak distances, the distances from the end of one house to the next were taken as 4, 8, 12, 16, 20, 25, 30, 40, 50, 75 and 100 feet. The peak-to-peak difference, therefore, was estimated as $1/2 \times$ house width (study house) + house-to-house difference + $1/2 \times$ house width (neighboring house). For simplicity, and since it makes no difference to the background, the neighboring house was assumed to be of the same configuration as the study house.

Finally, the differences in the height between a neighboring house and the study house was assumed to range between; taller by 1.5 stores and shorter by 1.5 stories, in increments of .25 stories. A story was taken as 10 feet.

Therefore, given:

a = $1/2 \times$ house width (feet)
d = peak-to-peak difference (feet)
h = height difference (feet)
 β = roof slope

$$b = a \tan \beta$$

By similar triangles

$$\begin{aligned} b^1 &= 1/2 * b = (a \tan \beta) / 2 \\ \text{and} \quad a^1 &= 1/2 a \end{aligned}$$

therefore

$$\begin{aligned} c &= b^1 + h = 1/2 a \tan \beta + h \\ d^1 &= d - a^1 = d - 1/2 a \end{aligned}$$

$$\tan \theta = \frac{1/2 a \tan \beta + h}{d - 1/2 a}$$

since $\delta = \beta$ and $\alpha = \theta + \delta$

$$\alpha = \beta + \arctan \left(\frac{1/2 a \tan \beta + h}{d - 1/2 a} \right)$$

$$\text{therefore, } 1-F = \frac{\alpha}{180}$$

Some interesting things to note:

- 1] The range of 1-F is 0 to .508
- 2] Flat roofs don't necessarily have 1-F = 0

A few examples of variation can be seen in Figure 1. The program can be seen in Figure 2, and the total output can be seen in Figures 3 through 14.

FIGURE 1

<u>ΔH</u>	<u>WIDTH</u>	<u>PEAK TO PEAK DIST.</u>	<u>15 DEG</u>	<u>1-F 30 DEG</u>	<u>45 DEG</u>
15'	29'	24'	.309	.407	.508
10'	20'	24'	.255	.356	.463
0'	20'	24'	.106	.215	.332
15'	20'	32'	.257	.353	.453
10'	20'	32'	.210	.308	.411
0'	20'	32'	.099	.201	.308
15'	28'	32'	.272	.374	.480
10'	28'	32'	.224	.330	.440
0'	28'	32'	.107	.218	.337
15'	28'	40'	.234	.333	.437
10'	28'	40'	.193	.295	.401
0'	28'	40'	.101	.205	.317

FIGURE 2

```

10 DEG
20 DIM X$(13,11),AS(13),RS(11),SS(11),OS(11)
30 MAT X=ZER
40 DISP "INPUT WIDTH HOUSE,SLOPE";
50 INPUT W,B
60 WRITE (15,70)
70 FORMAT 25X,"ESTIMATES OF 1-F",/
80 WRITE (15,90)W,B
90 FORMAT "HOUSE WIDTH =",F4.0," FEET",25X,"ROOF SLOPE =",F4.0," DEG"
100 PRINT
110 FOR N=1 TO 13
120 A(N)=10*(1.75-N*0.25)
130 NEXT N
140 READ R(1),R(2),R(3),R(4),R(5),R(6),R(7),R(8),R(9),R(10),R(11)
150 FOR N=1 TO 11
160 R(N)=R(N)+W
170 NEXT N
180 DATA 4,8,12,16,20,25,30,40,50,75,100
190 PRINT "RELATIONSHIP TO NEIGHBORING HOUSE"
200 WRITE (15,210)"*****"
210 FORMAT "*****"
220 WRITE (15,230)
230 FORMAT "HEIGHT*",/, "DIFF *",25X,"PEAK TO PEAK DIFFERENCE (FEET)"
240 WRITE (15,250)R(1),R(2),R(3),R(4),R(5),R(6),R(7),R(8),R(9),R(10),R(11)
250 FORMAT "FEET *",1X,11F6.0
260 WRITE (15,270)"*****"
270 FORMAT "*****"
280 FOR N=1 TO 13
290 FOR M=1 TO 11
300 X(N,M)=B+ATN((0.25*W*TAN(B)+A(N))/(R(M)-0.25*W))
310 IF X(N,M)<0 THEN 400
320 NEXT M
330 FOR M=1 TO 11
340 O(M)=X(N,M)/180
350 NEXT M
360 WRITE (15,370)A(N),O(1),O(2),O(3),O(4),O(5),O(6),O(7),O(8),O(9),O(10),O(11)
370 FORMAT F5.1,4X,11F6.3
380 NEXT N
390 STOP
400 X(N,M)=0
410 GOTO 320

```

FIGURE 3

ESTIMATES OF 1-F

HOUSE WIDTH = 20 FEET

ROOF SLOPE = 0 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)										
FEET *	24	28	32	36	40	45	50	60	70	95	120

15.0	0.213	0.184	0.161	0.143	0.129	0.114	0.102	0.085	0.072	0.053	0.041
12.5	0.185	0.158	0.138	0.122	0.109	0.096	0.086	0.071	0.060	0.044	0.034
10.0	0.154	0.131	0.113	0.099	0.089	0.078	0.070	0.057	0.049	0.035	0.028
7.5	0.120	0.100	0.086	0.076	0.067	0.059	0.053	0.043	0.037	0.026	0.021
5.0	0.082	0.068	0.058	0.051	0.045	0.040	0.035	0.029	0.024	0.018	0.014
2.5	0.042	0.034	0.029	0.026	0.023	0.020	0.018	0.014	0.012	0.009	0.007
0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-7.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-12.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-15.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

ESTIMATES OF 1-F

HOUSE WIDTH = 24 FEET

ROOF SLOPE = 0 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)										
FEET *	28	32	36	40	44	49	54	64	74	99	124

15.0	0.190	0.167	0.148	0.132	0.120	0.107	0.096	0.081	0.069	0.051	0.040
12.5	0.164	0.143	0.126	0.112	0.101	0.090	0.081	0.068	0.058	0.043	0.034
10.0	0.136	0.117	0.102	0.091	0.082	0.073	0.065	0.054	0.046	0.034	0.027
7.5	0.105	0.089	0.078	0.069	0.062	0.055	0.049	0.041	0.035	0.026	0.020
5.0	0.071	0.060	0.053	0.046	0.042	0.037	0.033	0.027	0.023	0.017	0.013
2.5	0.036	0.031	0.026	0.023	0.021	0.018	0.017	0.014	0.012	0.009	0.007
0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-7.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-12.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-15.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

FIGURE 4

ESTIMATES OF 1-F

HOUSE WIDTH = 28 FEET

ROOF SLOPE = 0 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	32	36	40	44	48	53	58	68	78	103	128

15.0	0.172	0.152	0.136	0.123	0.112	0.100	0.091	0.077	0.066	0.049	0.039
12.5	0.148	0.130	0.115	0.104	0.094	0.084	0.077	0.064	0.055	0.041	0.033
10.0	0.121	0.106	0.094	0.084	0.076	0.068	0.062	0.052	0.045	0.033	0.026
7.5	0.093	0.081	0.071	0.064	0.058	0.051	0.046	0.039	0.034	0.025	0.020
5.0	0.063	0.054	0.048	0.043	0.039	0.034	0.031	0.026	0.022	0.017	0.013
2.5	0.032	0.027	0.024	0.021	0.019	0.017	0.016	0.013	0.011	0.008	0.007
0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-7.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-12.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-15.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

ESTIMATES OF 1-F

HOUSE WIDTH = 32 FEET

ROOF SLOPE = 0 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	36	40	44	48	52	57	62	72	82	107	132

15.0	0.157	0.140	0.126	0.114	0.105	0.095	0.086	0.073	0.064	0.048	0.038
12.5	0.134	0.119	0.106	0.096	0.088	0.080	0.072	0.061	0.053	0.040	0.032
10.0	0.109	0.096	0.086	0.078	0.071	0.064	0.058	0.049	0.043	0.032	0.026
7.5	0.083	0.073	0.065	0.059	0.054	0.048	0.044	0.037	0.032	0.024	0.019
5.0	0.056	0.049	0.044	0.040	0.036	0.032	0.029	0.025	0.021	0.016	0.013
2.5	0.028	0.025	0.022	0.020	0.018	0.016	0.015	0.012	0.011	0.008	0.006
0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-7.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-12.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-15.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

FIGURE 5

ESTIMATES OF 1-F

HOUSE WIDTH = 40 FEET

ROOF SLOPE = 0 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	44	48	52	56	60	65	70	80	90	115	140

15.0	0.132	0.120	0.109	0.100	0.093	0.085	0.078	0.067	0.059	0.045	0.037
12.5	0.112	0.101	0.092	0.084	0.078	0.071	0.065	0.056	0.049	0.038	0.031
10.0	0.091	0.082	0.074	0.068	0.063	0.057	0.053	0.045	0.040	0.030	0.024
7.5	0.069	0.062	0.056	0.051	0.047	0.043	0.040	0.034	0.030	0.023	0.018
5.0	0.046	0.042	0.038	0.034	0.032	0.029	0.026	0.023	0.020	0.015	0.012
2.5	0.023	0.021	0.019	0.017	0.016	0.014	0.013	0.011	0.010	0.008	0.006
0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-7.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-12.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-15.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

ESTIMATES OF 1-F

HOUSE WIDTH = 50 FEET

ROOF SLOPE = 0 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	54	58	62	66	70	75	80	90	100	125	150

15.0	0.110	0.101	0.094	0.087	0.081	0.075	0.070	0.061	0.054	0.042	0.035
12.5	0.093	0.085	0.079	0.073	0.068	0.063	0.058	0.051	0.045	0.035	0.029
10.0	0.075	0.069	0.063	0.059	0.055	0.051	0.047	0.041	0.036	0.028	0.023
7.5	0.057	0.052	0.048	0.044	0.041	0.038	0.035	0.031	0.027	0.021	0.017
5.0	0.038	0.035	0.032	0.030	0.028	0.025	0.024	0.021	0.018	0.014	0.012
2.5	0.019	0.017	0.016	0.015	0.014	0.013	0.012	0.010	0.009	0.007	0.006
0.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-2.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-5.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-7.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-10.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-12.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-15.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

FIGURE 6

ESTIMATES OF 1-F

HOUSE WIDTH = 20 FEET

ROOF SLOPE = 15 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	24	28	32	36	40	45	50	60	70	95	120

15.0	0.309	0.280	0.257	0.238	0.222	0.207	0.194	0.175	0.162	0.141	0.128
12.5	0.284	0.256	0.234	0.217	0.203	0.189	0.178	0.162	0.150	0.132	0.121
10.0	0.255	0.229	0.210	0.195	0.183	0.171	0.162	0.148	0.138	0.123	0.115
7.5	0.222	0.200	0.184	0.172	0.162	0.153	0.145	0.134	0.126	0.114	0.108
5.0	0.186	0.169	0.157	0.148	0.140	0.133	0.128	0.120	0.114	0.106	0.101
2.5	0.147	0.136	0.128	0.123	0.118	0.114	0.110	0.106	0.102	0.097	0.094
0.0	0.106	0.102	0.099	0.097	0.096	0.094	0.093	0.091	0.090	0.088	0.087
-2.5	0.064	0.067	0.070	0.071	0.073	0.074	0.075	0.077	0.078	0.079	0.080
-5.0	0.023	0.033	0.040	0.046	0.050	0.054	0.057	0.062	0.065	0.070	0.073
-7.5	0.000	0.000	0.012	0.021	0.028	0.035	0.040	0.048	0.053	0.062	0.066
-10.0	0.000	0.000	0.000	0.000	0.006	0.015	0.023	0.034	0.041	0.053	0.059
-12.5	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.020	0.029	0.044	0.053
-15.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.017	0.035	0.046

ESTIMATES OF 1-F

HOUSE WIDTH = 24 FEET

ROOF SLOPE = 15 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	28	32	36	40	44	49	54	64	74	99	124

15.0	0.289	0.264	0.244	0.228	0.214	0.201	0.189	0.172	0.160	0.140	0.128
12.5	0.265	0.242	0.223	0.209	0.196	0.184	0.174	0.159	0.148	0.131	0.121
10.0	0.238	0.217	0.201	0.188	0.178	0.167	0.159	0.146	0.137	0.123	0.115
7.5	0.208	0.191	0.177	0.167	0.158	0.150	0.143	0.133	0.126	0.114	0.108
5.0	0.176	0.163	0.152	0.144	0.138	0.132	0.127	0.119	0.114	0.106	0.101
2.5	0.142	0.133	0.127	0.122	0.118	0.114	0.111	0.106	0.103	0.097	0.094
0.0	0.107	0.103	0.100	0.098	0.097	0.095	0.094	0.092	0.091	0.089	0.088
-2.5	0.070	0.072	0.074	0.075	0.076	0.077	0.077	0.078	0.079	0.080	0.081
-5.0	0.035	0.042	0.047	0.052	0.055	0.058	0.061	0.065	0.067	0.072	0.074
-7.5	0.000	0.012	0.022	0.029	0.034	0.040	0.044	0.051	0.056	0.063	0.067
-10.0	0.000	0.000	0.000	0.006	0.014	0.022	0.028	0.038	0.044	0.055	0.061
-12.5	0.000	0.000	0.000	0.000	0.000	0.004	0.012	0.024	0.033	0.046	0.054
-15.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.021	0.038	0.047

FIGURE 7

ESTIMATES OF 1-F

HOUSE WIDTH = 28 FEET

ROOF SLOPE = 15 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)										
FEET *	32	36	40	44	48	53	58	68	78	103	128

15.0	0.272	0.251	0.234	0.220	0.208	0.195	0.185	0.169	0.158	0.139	0.127
12.5	0.249	0.230	0.214	0.201	0.191	0.180	0.171	0.157	0.147	0.131	0.121
10.0	0.224	0.207	0.193	0.182	0.173	0.164	0.156	0.145	0.136	0.123	0.114
7.5	0.198	0.183	0.171	0.162	0.155	0.147	0.141	0.132	0.125	0.114	0.108
5.0	0.169	0.157	0.149	0.142	0.136	0.131	0.126	0.119	0.114	0.106	0.101
2.5	0.138	0.131	0.125	0.121	0.117	0.114	0.111	0.106	0.103	0.098	0.095
0.0	0.107	0.104	0.101	0.099	0.098	0.096	0.095	0.093	0.092	0.090	0.088
-2.5	0.075	0.076	0.077	0.078	0.078	0.079	0.079	0.080	0.081	0.081	0.082
-5.0	0.044	0.049	0.053	0.057	0.059	0.062	0.064	0.067	0.069	0.073	0.075
-7.5	0.013	0.022	0.030	0.035	0.040	0.045	0.048	0.054	0.058	0.065	0.069
-10.0	0.000	0.000	0.006	0.015	0.021	0.028	0.033	0.041	0.047	0.056	0.062
-12.5	0.000	0.000	0.000	0.000	0.003	0.011	0.018	0.028	0.036	0.048	0.055
-15.0	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.016	0.025	0.040	0.049

ESTIMATES OF 1-F

HOUSE WIDTH = 32 FEET

ROOF SLOPE = 15 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)										
FEET *	36	40	44	48	52	57	62	72	82	107	132

15.0	0.258	0.240	0.225	0.212	0.202	0.190	0.181	0.167	0.156	0.138	0.127
12.5	0.237	0.220	0.206	0.195	0.186	0.176	0.168	0.155	0.146	0.130	0.121
10.0	0.214	0.199	0.187	0.177	0.169	0.161	0.154	0.143	0.135	0.122	0.114
7.5	0.189	0.177	0.167	0.159	0.152	0.145	0.140	0.131	0.125	0.114	0.108
5.0	0.163	0.153	0.146	0.140	0.135	0.129	0.125	0.119	0.114	0.106	0.102
2.5	0.136	0.129	0.124	0.120	0.117	0.113	0.111	0.106	0.103	0.098	0.095
0.0	0.108	0.105	0.102	0.100	0.099	0.097	0.096	0.094	0.093	0.090	0.089
-2.5	0.079	0.080	0.080	0.080	0.081	0.081	0.081	0.082	0.082	0.082	0.082
-5.0	0.051	0.055	0.058	0.061	0.063	0.065	0.067	0.069	0.071	0.074	0.076
-7.5	0.023	0.031	0.036	0.041	0.045	0.049	0.052	0.057	0.060	0.066	0.070
-10.0	0.000	0.007	0.015	0.022	0.027	0.033	0.037	0.044	0.050	0.058	0.063
-12.5	0.000	0.000	0.000	0.003	0.010	0.017	0.023	0.032	0.039	0.050	0.057
-15.0	0.000	0.000	0.000	0.000	0.000	0.002	0.009	0.020	0.029	0.042	0.050

FIGURE 8

ESTIMATES OF 1-F

HOUSE WIDTH = 40 FEET

ROOF SLOPE = 15 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	44	48	52	56	60	65	70	80	90	115	140

15.0	0.236	0.222	0.210	0.200	0.192	0.182	0.175	0.162	0.153	0.136	0.126
12.5	0.217	0.204	0.194	0.185	0.177	0.169	0.162	0.151	0.143	0.129	0.120
10.0	0.197	0.186	0.177	0.169	0.162	0.155	0.150	0.140	0.133	0.122	0.114
7.5	0.176	0.167	0.159	0.153	0.147	0.142	0.137	0.129	0.124	0.114	0.108
5.0	0.154	0.147	0.141	0.136	0.132	0.127	0.124	0.118	0.114	0.107	0.102
2.5	0.131	0.126	0.122	0.119	0.116	0.113	0.111	0.107	0.104	0.099	0.096
0.0	0.108	0.106	0.104	0.102	0.100	0.099	0.098	0.096	0.094	0.091	0.090
-2.5	0.085	0.085	0.085	0.085	0.084	0.084	0.084	0.084	0.084	0.084	0.084
-5.0	0.062	0.064	0.066	0.067	0.069	0.070	0.071	0.073	0.074	0.076	0.078
-7.5	0.039	0.043	0.047	0.050	0.053	0.056	0.058	0.061	0.064	0.069	0.072
-10.0	0.016	0.023	0.028	0.033	0.037	0.041	0.045	0.050	0.054	0.061	0.065
-12.5	0.000	0.003	0.010	0.016	0.022	0.027	0.032	0.039	0.044	0.054	0.059
-15.0	0.000	0.000	0.000	0.000	0.006	0.013	0.019	0.028	0.035	0.046	0.053

ESTIMATES OF 1-F

HOUSE WIDTH = 50 FEET

ROOF SLOPE = 15 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	54	58	62	66	70	75	80	90	100	125	150

15.0	0.216	0.205	0.196	0.189	0.182	0.174	0.168	0.157	0.149	0.135	0.126
12.5	0.199	0.190	0.182	0.175	0.169	0.162	0.157	0.148	0.140	0.128	0.120
10.0	0.182	0.174	0.167	0.161	0.156	0.150	0.145	0.138	0.132	0.121	0.114
7.5	0.165	0.158	0.152	0.147	0.143	0.138	0.134	0.128	0.123	0.114	0.108
5.0	0.147	0.141	0.137	0.133	0.129	0.126	0.123	0.117	0.114	0.107	0.103
2.5	0.128	0.124	0.121	0.118	0.116	0.113	0.111	0.107	0.105	0.100	0.097
0.0	0.109	0.107	0.105	0.103	0.102	0.100	0.099	0.097	0.096	0.093	0.091
-2.5	0.090	0.089	0.089	0.088	0.088	0.088	0.088	0.087	0.087	0.086	0.085
-5.0	0.071	0.072	0.073	0.074	0.074	0.075	0.076	0.077	0.077	0.079	0.080
-7.5	0.052	0.054	0.057	0.059	0.060	0.062	0.064	0.066	0.068	0.072	0.074
-10.0	0.033	0.037	0.041	0.044	0.047	0.050	0.052	0.056	0.059	0.065	0.068
-12.5	0.014	0.020	0.025	0.029	0.033	0.037	0.040	0.046	0.050	0.057	0.062
-15.0	0.000	0.004	0.010	0.015	0.020	0.025	0.029	0.036	0.041	0.050	0.056

FIGURE 9

ESTIMATES OF 1-F

HOUSE WIDTH = 20 FEET

ROOF SLOPE = 30 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	24	28	32	36	40	45	50	60	70	95	120

15.0	0.407	0.377	0.353	0.333	0.317	0.301	0.287	0.267	0.252	0.229	0.216
12.5	0.383	0.354	0.332	0.313	0.299	0.284	0.272	0.253	0.241	0.221	0.209
10.0	0.356	0.329	0.308	0.292	0.279	0.266	0.255	0.240	0.229	0.212	0.202
7.5	0.326	0.302	0.284	0.270	0.258	0.248	0.239	0.226	0.217	0.203	0.195
5.0	0.292	0.272	0.257	0.246	0.237	0.229	0.222	0.212	0.205	0.194	0.188
2.5	0.255	0.240	0.229	0.221	0.215	0.209	0.205	0.198	0.193	0.186	0.182
0.0	0.215	0.206	0.201	0.196	0.193	0.190	0.187	0.183	0.181	0.177	0.175
-2.5	0.173	0.172	0.171	0.171	0.170	0.170	0.169	0.169	0.169	0.168	0.168
-5.0	0.131	0.138	0.142	0.145	0.147	0.150	0.152	0.154	0.156	0.159	0.161
-7.5	0.091	0.104	0.113	0.120	0.125	0.130	0.134	0.140	0.144	0.150	0.154
-10.0	0.053	0.071	0.085	0.095	0.103	0.111	0.117	0.126	0.132	0.142	0.147
-12.5	0.018	0.041	0.058	0.071	0.081	0.092	0.100	0.112	0.120	0.133	0.140
-15.0	0.000	0.012	0.032	0.048	0.061	0.073	0.083	0.098	0.108	0.124	0.133

ESTIMATES OF 1-F

HOUSE WIDTH = 24 FEET

ROOF SLOPE = 30 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	28	32	36	40	44	49	54	64	74	99	124

15.0	0.389	0.363	0.342	0.325	0.311	0.296	0.284	0.265	0.251	0.229	0.216
12.5	0.366	0.342	0.322	0.306	0.293	0.280	0.269	0.252	0.240	0.221	0.209
10.0	0.341	0.319	0.301	0.287	0.275	0.263	0.254	0.239	0.229	0.212	0.203
7.5	0.314	0.294	0.278	0.266	0.256	0.246	0.238	0.226	0.218	0.204	0.196
5.0	0.284	0.267	0.254	0.244	0.236	0.229	0.222	0.213	0.206	0.196	0.189
2.5	0.251	0.238	0.229	0.222	0.216	0.211	0.206	0.199	0.195	0.187	0.183
0.0	0.216	0.209	0.203	0.199	0.196	0.192	0.190	0.186	0.183	0.179	0.176
-2.5	0.181	0.178	0.177	0.176	0.175	0.174	0.173	0.172	0.171	0.170	0.169
-5.0	0.144	0.148	0.150	0.152	0.154	0.155	0.156	0.158	0.159	0.161	0.163
-7.5	0.109	0.118	0.124	0.129	0.133	0.137	0.140	0.145	0.148	0.153	0.156
-10.0	0.075	0.088	0.098	0.106	0.112	0.119	0.124	0.131	0.136	0.144	0.149
-12.5	0.043	0.060	0.074	0.084	0.092	0.101	0.107	0.117	0.125	0.136	0.142
-15.0	0.013	0.034	0.050	0.063	0.073	0.083	0.092	0.104	0.113	0.127	0.136

FIGURE 10

ESTIMATES OF 1-F

HOUSE WIDTH = 28 FEET

ROOF SLOPE = 30 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)										
FEET *	32	36	40	44	48	53	58	68	78	103	128

15.0	0.374	0.352	0.333	0.318	0.305	0.292	0.280	0.263	0.250	0.229	0.216
12.5	0.353	0.332	0.315	0.300	0.289	0.277	0.267	0.251	0.240	0.221	0.210
10.0	0.330	0.310	0.295	0.282	0.272	0.261	0.252	0.239	0.229	0.213	0.203
7.5	0.304	0.287	0.274	0.263	0.254	0.245	0.238	0.226	0.218	0.205	0.197
5.0	0.277	0.263	0.252	0.243	0.236	0.228	0.223	0.214	0.207	0.197	0.190
2.5	0.248	0.237	0.229	0.222	0.217	0.212	0.207	0.201	0.196	0.188	0.184
0.0	0.218	0.211	0.205	0.201	0.198	0.195	0.192	0.188	0.185	0.180	0.177
-2.5	0.186	0.184	0.182	0.180	0.179	0.177	0.176	0.175	0.174	0.172	0.171
-5.0	0.154	0.156	0.157	0.158	0.159	0.160	0.161	0.162	0.162	0.163	0.164
-7.5	0.123	0.129	0.133	0.137	0.140	0.143	0.145	0.149	0.151	0.155	0.158
-10.0	0.092	0.102	0.110	0.116	0.121	0.126	0.130	0.136	0.140	0.147	0.151
-12.5	0.063	0.076	0.087	0.095	0.102	0.109	0.114	0.123	0.129	0.139	0.144
-15.0	0.035	0.052	0.065	0.075	0.084	0.092	0.099	0.110	0.118	0.130	0.138

ESTIMATES OF 1-F

HOUSE WIDTH = 32 FEET

ROOF SLOPE = 30 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)										
FEET *	36	40	44	48	52	57	62	72	82	107	132

15.0	0.361	0.342	0.325	0.312	0.300	0.288	0.278	0.261	0.249	0.229	0.217
12.5	0.341	0.323	0.308	0.295	0.285	0.274	0.264	0.250	0.239	0.221	0.210
10.0	0.320	0.303	0.289	0.278	0.269	0.259	0.251	0.238	0.229	0.213	0.204
7.5	0.297	0.282	0.270	0.260	0.252	0.244	0.237	0.226	0.218	0.205	0.198
5.0	0.272	0.260	0.250	0.242	0.235	0.228	0.223	0.214	0.208	0.197	0.191
2.5	0.246	0.236	0.229	0.223	0.218	0.213	0.208	0.202	0.197	0.190	0.185
0.0	0.219	0.212	0.207	0.203	0.200	0.197	0.194	0.190	0.187	0.182	0.179
-2.5	0.191	0.188	0.185	0.184	0.182	0.180	0.179	0.177	0.176	0.173	0.172
-5.0	0.162	0.163	0.163	0.164	0.164	0.164	0.164	0.165	0.165	0.165	0.166
-7.5	0.134	0.138	0.141	0.144	0.146	0.148	0.150	0.152	0.154	0.157	0.159
-10.0	0.106	0.114	0.119	0.124	0.128	0.132	0.135	0.140	0.144	0.149	0.153
-12.5	0.079	0.090	0.098	0.105	0.110	0.116	0.121	0.128	0.133	0.141	0.146
-15.0	0.054	0.067	0.077	0.086	0.093	0.100	0.106	0.115	0.122	0.133	0.140

FIGURE 11

ESTIMATES OF 1-F

HOUSE WIDTH = 40 FEET

ROOF SLOPE = 30 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	44	48	52	56	60	65	70	80	90	115	140

15.0	0.341	0.326	0.313	0.302	0.292	0.282	0.273	0.258	0.248	0.229	0.217
12.5	0.324	0.309	0.297	0.287	0.278	0.269	0.261	0.248	0.238	0.222	0.211
10.0	0.305	0.292	0.281	0.272	0.264	0.256	0.248	0.237	0.229	0.214	0.205
7.5	0.285	0.274	0.264	0.256	0.249	0.242	0.236	0.226	0.219	0.207	0.199
5.0	0.264	0.255	0.247	0.240	0.234	0.228	0.223	0.215	0.209	0.199	0.193
2.5	0.243	0.235	0.229	0.223	0.219	0.214	0.210	0.204	0.199	0.192	0.187
0.0	0.220	0.215	0.210	0.206	0.203	0.200	0.197	0.193	0.190	0.184	0.181
-2.5	0.197	0.194	0.191	0.189	0.187	0.186	0.184	0.182	0.180	0.177	0.175
-5.0	0.174	0.173	0.173	0.172	0.172	0.171	0.171	0.170	0.170	0.169	0.169
-7.5	0.151	0.152	0.154	0.155	0.156	0.157	0.158	0.159	0.160	0.161	0.162
-10.0	0.127	0.131	0.135	0.138	0.140	0.142	0.144	0.147	0.150	0.154	0.156
-12.5	0.104	0.111	0.116	0.120	0.124	0.128	0.131	0.136	0.140	0.146	0.150
-15.0	0.082	0.091	0.098	0.104	0.109	0.114	0.118	0.125	0.130	0.139	0.144

ESTIMATES OF 1-F

HOUSE WIDTH = 50 FEET

ROOF SLOPE = 30 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *											
PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	54	58	62	66	70	75	80	90	100	125	150

15.0	0.323	0.311	0.301	0.292	0.284	0.275	0.268	0.256	0.246	0.229	0.218
12.5	0.308	0.297	0.287	0.279	0.272	0.264	0.257	0.246	0.237	0.222	0.212
10.0	0.292	0.282	0.273	0.266	0.259	0.252	0.246	0.236	0.229	0.215	0.206
7.5	0.275	0.266	0.259	0.252	0.246	0.240	0.235	0.226	0.220	0.208	0.201
5.0	0.258	0.250	0.244	0.238	0.233	0.228	0.224	0.216	0.211	0.201	0.195
2.5	0.240	0.234	0.228	0.224	0.220	0.216	0.212	0.206	0.202	0.194	0.189
0.0	0.221	0.217	0.213	0.209	0.206	0.203	0.201	0.196	0.193	0.187	0.183
-2.5	0.203	0.200	0.197	0.195	0.193	0.191	0.189	0.186	0.184	0.180	0.178
-5.0	0.184	0.182	0.181	0.180	0.179	0.178	0.177	0.176	0.175	0.173	0.172
-7.5	0.164	0.165	0.165	0.165	0.165	0.165	0.165	0.165	0.166	0.166	0.166
-10.0	0.145	0.147	0.149	0.150	0.151	0.153	0.154	0.155	0.157	0.159	0.160
-12.5	0.126	0.130	0.133	0.135	0.138	0.140	0.142	0.145	0.147	0.152	0.154
-15.0	0.108	0.113	0.117	0.121	0.124	0.127	0.130	0.135	0.138	0.145	0.149

FIGURE 12

ESTIMATES OF 1-F

HOUSE WIDTH = 20 FEET

ROOF SLOPE = 45 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)										
FEET *	24	28	32	36	40	45	50	60	70	95	120

15.0	0.508	0.478	0.453	0.432	0.415	0.398	0.383	0.361	0.345	0.320	0.305
12.5	0.487	0.457	0.433	0.414	0.398	0.381	0.368	0.348	0.334	0.311	0.298
10.0	0.463	0.434	0.411	0.393	0.379	0.364	0.352	0.335	0.322	0.303	0.291
7.5	0.435	0.408	0.388	0.372	0.359	0.346	0.336	0.321	0.310	0.294	0.284
5.0	0.404	0.381	0.363	0.349	0.339	0.328	0.320	0.307	0.299	0.285	0.278
2.5	0.370	0.350	0.336	0.326	0.317	0.309	0.303	0.293	0.287	0.276	0.271
0.0	0.332	0.318	0.308	0.301	0.295	0.290	0.285	0.279	0.274	0.268	0.264
-2.5	0.292	0.284	0.279	0.276	0.273	0.270	0.268	0.264	0.262	0.259	0.257
-5.0	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250
-7.5	0.208	0.216	0.221	0.224	0.227	0.230	0.232	0.236	0.238	0.241	0.243
-10.0	0.168	0.182	0.192	0.199	0.205	0.210	0.215	0.221	0.226	0.232	0.236
-12.5	0.130	0.150	0.164	0.174	0.183	0.191	0.197	0.207	0.213	0.224	0.229
-15.0	0.096	0.119	0.137	0.151	0.161	0.172	0.180	0.193	0.201	0.215	0.222

ESTIMATES OF 1-F

HOUSE WIDTH = 24 FEET

ROOF SLOPE = 45 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)										
FEET *	28	32	36	40	44	49	54	64	74	99	124

15.0	0.493	0.466	0.444	0.426	0.411	0.395	0.381	0.361	0.345	0.321	0.306
12.5	0.473	0.447	0.426	0.409	0.394	0.379	0.367	0.348	0.335	0.313	0.300
10.0	0.450	0.426	0.406	0.390	0.377	0.363	0.352	0.336	0.324	0.304	0.293
7.5	0.425	0.402	0.385	0.370	0.359	0.347	0.337	0.323	0.312	0.296	0.286
5.0	0.398	0.377	0.362	0.350	0.340	0.330	0.322	0.310	0.301	0.287	0.280
2.5	0.367	0.351	0.338	0.328	0.320	0.312	0.306	0.296	0.290	0.279	0.273
0.0	0.335	0.322	0.313	0.306	0.300	0.294	0.290	0.283	0.278	0.271	0.266
-2.5	0.300	0.293	0.287	0.283	0.279	0.276	0.273	0.269	0.266	0.262	0.259
-5.0	0.264	0.262	0.261	0.259	0.258	0.257	0.257	0.255	0.255	0.253	0.253
-7.5	0.228	0.232	0.234	0.236	0.237	0.239	0.240	0.242	0.243	0.245	0.246
-10.0	0.193	0.201	0.208	0.213	0.217	0.220	0.224	0.228	0.231	0.236	0.239
-12.5	0.159	0.172	0.182	0.190	0.196	0.202	0.207	0.214	0.220	0.228	0.232
-15.0	0.126	0.144	0.157	0.168	0.176	0.184	0.191	0.201	0.208	0.219	0.226

FIGURE 13

ESTIMATES OF 1-F

HOUSE WIDTH = 28 FEET

ROOF SLOPE = 45 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*												
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	32	36	40	44	48	53	58	68	78	103	128	

15.0	0.480	0.457	0.437	0.421	0.407	0.392	0.380	0.360	0.346	0.322	0.307	
12.5	0.461	0.438	0.420	0.404	0.391	0.378	0.366	0.348	0.335	0.314	0.301	
10.0	0.440	0.419	0.401	0.387	0.375	0.363	0.352	0.337	0.325	0.306	0.294	
7.5	0.417	0.398	0.382	0.369	0.358	0.347	0.338	0.324	0.314	0.298	0.288	
5.0	0.392	0.375	0.361	0.350	0.341	0.331	0.324	0.312	0.303	0.290	0.281	
2.5	0.366	0.351	0.339	0.330	0.322	0.315	0.309	0.299	0.292	0.281	0.275	
0.0	0.337	0.325	0.317	0.310	0.304	0.298	0.293	0.286	0.281	0.273	0.268	
-2.5	0.307	0.299	0.293	0.289	0.285	0.281	0.278	0.273	0.270	0.265	0.262	
-5.0	0.275	0.272	0.269	0.267	0.266	0.264	0.262	0.260	0.259	0.257	0.255	
-7.5	0.244	0.245	0.245	0.246	0.246	0.247	0.247	0.247	0.248	0.248	0.249	
-10.0	0.212	0.217	0.221	0.224	0.227	0.229	0.231	0.234	0.237	0.240	0.242	
-12.5	0.181	0.190	0.197	0.203	0.208	0.212	0.216	0.221	0.225	0.232	0.236	
-15.0	0.151	0.164	0.174	0.182	0.189	0.195	0.200	0.208	0.214	0.224	0.229	

ESTIMATES OF 1-F

HOUSE WIDTH = 32 FEET

ROOF SLOPE = 45 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*												
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)											
FEET *	36	40	44	48	52	57	62	72	82	107	132	

15.0	0.469	0.448	0.431	0.416	0.403	0.390	0.378	0.360	0.346	0.323	0.308	
12.5	0.451	0.431	0.415	0.401	0.389	0.376	0.365	0.349	0.336	0.315	0.302	
10.0	0.432	0.413	0.398	0.385	0.374	0.362	0.352	0.337	0.326	0.307	0.296	
7.5	0.411	0.394	0.379	0.368	0.358	0.348	0.339	0.326	0.316	0.299	0.290	
5.0	0.388	0.373	0.360	0.350	0.341	0.333	0.325	0.314	0.305	0.292	0.283	
2.5	0.364	0.351	0.340	0.332	0.325	0.317	0.311	0.302	0.295	0.284	0.277	
0.0	0.339	0.328	0.320	0.313	0.307	0.302	0.297	0.290	0.284	0.276	0.271	
-2.5	0.312	0.304	0.298	0.293	0.290	0.286	0.282	0.277	0.274	0.268	0.264	
-5.0	0.284	0.280	0.276	0.274	0.272	0.269	0.268	0.265	0.263	0.260	0.258	
-7.5	0.256	0.255	0.254	0.254	0.254	0.253	0.253	0.252	0.252	0.252	0.251	
-10.0	0.227	0.230	0.232	0.234	0.236	0.237	0.238	0.240	0.241	0.244	0.245	
-12.5	0.199	0.206	0.210	0.214	0.218	0.221	0.224	0.228	0.231	0.236	0.238	
-15.0	0.172	0.181	0.189	0.195	0.200	0.205	0.209	0.215	0.220	0.228	0.232	

FIGURE 14

ESTIMATES OF 1-F

HOUSE WIDTH = 40 FEET

ROOF SLOPE = 45 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)										
FEET *	44	48	52	56	60	65	70	80	90	115	140

15.0	0.452	0.435	0.421	0.408	0.398	0.386	0.376	0.359	0.346	0.324	0.310
12.5	0.436	0.420	0.407	0.395	0.385	0.374	0.364	0.349	0.337	0.317	0.305
10.0	0.419	0.404	0.391	0.381	0.371	0.361	0.352	0.339	0.328	0.310	0.299
7.5	0.401	0.387	0.376	0.366	0.357	0.348	0.340	0.328	0.319	0.303	0.293
5.0	0.382	0.370	0.359	0.350	0.343	0.335	0.328	0.317	0.309	0.295	0.287
2.5	0.362	0.351	0.342	0.334	0.328	0.321	0.315	0.306	0.299	0.288	0.281
0.0	0.341	0.332	0.324	0.318	0.313	0.307	0.303	0.295	0.290	0.280	0.274
-2.5	0.319	0.312	0.306	0.301	0.297	0.293	0.290	0.284	0.280	0.273	0.268
-5.0	0.296	0.292	0.288	0.284	0.282	0.279	0.276	0.273	0.270	0.265	0.262
-7.5	0.273	0.271	0.269	0.267	0.266	0.264	0.263	0.261	0.260	0.258	0.256
-10.0	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250
-12.5	0.227	0.229	0.231	0.233	0.234	0.236	0.237	0.239	0.240	0.242	0.244
-15.0	0.204	0.208	0.212	0.216	0.218	0.221	0.224	0.227	0.230	0.235	0.238

ESTIMATES OF 1-F

HOUSE WIDTH = 50 FEET

ROOF SLOPE = 45 DEG

RELATIONSHIP TO NEIGHBORING HOUSE

HEIGHT*											
DIFF *	PEAK TO PEAK DIFFERENCE (FEET)										
FEET *	54	58	62	66	70	75	80	90	100	125	150

15.0	0.436	0.423	0.411	0.401	0.392	0.382	0.373	0.359	0.347	0.326	0.313
12.5	0.423	0.410	0.399	0.389	0.381	0.371	0.363	0.349	0.339	0.320	0.307
10.0	0.408	0.396	0.386	0.377	0.369	0.360	0.352	0.340	0.330	0.313	0.302
7.5	0.393	0.382	0.372	0.364	0.357	0.349	0.342	0.330	0.322	0.306	0.296
5.0	0.377	0.367	0.358	0.351	0.344	0.337	0.331	0.321	0.313	0.299	0.290
2.5	0.360	0.351	0.344	0.337	0.331	0.325	0.320	0.311	0.304	0.292	0.285
0.0	0.343	0.335	0.329	0.323	0.318	0.313	0.308	0.301	0.295	0.285	0.279
-2.5	0.325	0.319	0.313	0.309	0.305	0.301	0.297	0.291	0.286	0.278	0.273
-5.0	0.307	0.302	0.298	0.294	0.291	0.288	0.285	0.281	0.277	0.271	0.267
-7.5	0.288	0.285	0.282	0.280	0.278	0.275	0.274	0.271	0.268	0.264	0.262
-10.0	0.269	0.267	0.266	0.265	0.264	0.263	0.262	0.260	0.259	0.257	0.256
-12.5	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250	0.250
-15.0	0.231	0.233	0.234	0.235	0.236	0.237	0.238	0.240	0.241	0.243	0.244

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

APPENDIX B

DATA COLLECTION PROCEDURES

This appendix is intended to serve as a review of the important parameters to consider in collecting data to be analyzed using the techniques suggested in this report.

B.1 Thermal Procedures

Data collection should employ a DC restored-manual gain infrared scanner. The scanner should be carefully calibrated in the laboratory. Calibration should concentrate on the blackbody setting versus temperature relationship and the gain versus gain setting relationship as these govern the internal scanner calibration. Scanners having two fully calibrated blackbodies or one blackbody and a calibrated gain control should be used. Scanners without blackbodies or scanners that reference to housing temperature cannot be adequately calibrated for the applications discussed here.

The system should have some form of roll compensation and be flown such that ground spot sizes at the nadir are less than or equal to 2 feet for residential structures and less than or equal to 2.5 feet for commercial structures.

All data collected should have step wedges applied at periodic intervals for all v/H settings employed in data collection.

A profile should be flown at least once during a mission and preferably before and after the data collection effort. The profile shall consist of 3 to 5 passes over a water body at decreasing altitudes from the flight altitude to a minimum value of about 100 ft. AGL (maintain fixed v/H). The flight lines should be selected to image the same points in the water on consecutive passes and water temperature differences should be optimized. Thermal discharges are particularly useful if they can be overflown. At flight altitude, at least one offset flight line from the profile lines should be flown as discussed in Section 3.

Detailed flight logs should be kept with particular attention to instrument setting (especially gain, blackbody, v/H, and DC level).

All data should be collected at night at least four hours after sunset. Weather should be such that air temperatures are at least 20°F below expected room temperatures, skies should be clear and winds below about five miles per hour at roof level. Care must be taken that the moisture in the roofs is not in the process of freezing and that the dew point is not reached. In addition, the roofs should be clear of surface moisture. In general, colder, clearer, calmer, and drier nights represent better data collection conditions.

All film should be machine processed to ensure uniform developing.

B.2 Photographic Procedures

If photometric interpretation is to be performed, then several procedures must be followed in collecting daytime color photography. The camera-filter combination should have known fall-off properties. In general, total fields-of-view of less than 40° are preferred. Wider fields can introduce additional variables that are time-consuming to account for. Color positive film should be used (EK2448). Step wedges should be placed on each roll of film and all film should be machine processed. Data should be collected under clear conditions with high (winter) sun elevations. The imagery should be collected at a scale that is convenient for densitometric analysis. For most common 1-mm aperture densitometers, scales of about 1:5000 are best. Analysis can be simplified if reflectance panels can be placed on the ground at the time of the overflight.

APPENDIX C
COMPUTER PROGRAMS FOR DATA ANALYSIS
AND THEORETICAL MODELING

In order to handle and analyze the data generated in the Heat Loss research effort, many programs and analysis methodologies were devised. This appendix will briefly touch upon the most important.

C.1 Theoretical and Calibration Methods

As described in Section 2, the energy in watts radiating from a blackbody is equal to

$$W = \sigma T^4 \quad (C-1)$$

where W = watts per square area

σ = Stefan-Boltzmann

T = temperature in degree Kelvin

Equation C-1 gives the total spectral energy. However, scanners generally look at discrete parts of the spectra. Since the scanner in use looks at either the 3 to 5 micron pass or the 8 to 14 micron pass, the blackbody radiation in those spectral bands was of concern. The radiation between any two wavelengths at a given temperature is equal to

$$W = (D\lambda_N - D\lambda_N^{-1})\sigma T^4 \quad (C-2)$$

where $D\lambda_N$ = the percent of area under the blackbody radiation curve from 0 microns to N microns

For each $\lambda \cdot T$ there is a unique $D\lambda$ summarized in Pivovonski and Nagel, 1961, (Reference 13). The $D\lambda$'s have been catalogued and stored for temperatures ranging from 70 to 320 degrees Kelvin for 3, 5, 8 and 14 microns. They have also been put into Equation C-2 and the resultant W 's for 3 to 5 and 8 to 14 have been stored. Storage information can be seen in Table C.1-1.

Calibration of thermal imagery is an essential component of rigorous analysis for heat loss, as discussed in Section 3. The theoretically derived equations have been standardized into a computer program that inputs the step-wedge and internal scanner calibration data, apparent temperatures at angle and altitude and outputs the atmospheric and background calibration. A brief description of the thermal calibration tape can be seen in Table C.1-2

C.2 Material Identification

In order to analyze heat loss on a house-to-house basis, the material of the roof must be identified in order to determine the emissivity. Ideally, this will be done from aerial imagery. Therefore, several methods of identification were attempted.

C.2.A Bi-Band Ratioing

The apparent temperatures were read for 150 different roofs, including commercial and residential, corrected for atmospheric and angular effects and converted to equivalent blackbody radiance values. These values were then ratioed and plotted against the material type to give the plot seen in Figure 5.B-1. The data and relevant programs are summarized in Table C.2-1.

C.2.B Photometric ID Techniques

Available color imagery was calibrated and the red, green and blue reflectances for a number of commercial and residential roofs were determined. Using the SAS "discrim" procedure (see Reference 1), a multivariate discriminate analysis was performed. The red, green and blue reflectances, and the red to green, green to blue and red to blue reflectance ratios were used as classification variables and material type was used as the class descriptor. The test was done such that a test of homogeneity of within-group covariance matrices was done in order to determine whether the within-group covariance matrix or the pooled covariance matrix was to be used to determine the measure of generalized squared distance. Test cases using an independent data set were also run.

The same test on the same data was also run with the addition of the 8-14 μ m to 3-5 μ m relative radiance ratios as an additional classification variable.

The data used in these tests is preserved on computer cards, and the results are discussed in Section 5.

C.3 Emissivity

As discussed in Section 4, to determine emissivity, radiant energy is mathematically compared to contact temperature which has been converted to an equivalent blackbody radiation value. The program written to do this inputs the radiometer reading and the thermistor readings for various temperatures going from below ambient room temperature to above ambient room temperature. It then converts, through calibration curves for the various instruments, these readings to radiant energy values and does the regression. The output is the overall slope, and the slope from below ambient to ambient and from ambient to above ambient. These slopes are then compared to slopes obtained from a blackbody with known emissivity to obtain the sample emissivity. The program is stored on Emissivity Tape No. 2, File 10.

C.4 Error Analysis

One of the more important areas of any analysis is the determination of the accuracy to which variables must be known for a required overall accuracy. This was accomplished in the heat loss program through error analysis using the partial derivatives of temperature with respect to the various parameters.

The programs, where they can be found and what they do, are summarized in Table C.4-1. Typical results can be seen in Tables 6.B-1 and 6.C-1.

C.5 Heat Loss Equations

This part of the effort was the most theoretical in terms of programming. The two operative equations, modified from ASHRAE and others (McPhee, 1972), were:

$$Q = hc(T_s - T_a) + F(\epsilon\sigma T_s^4 - \epsilon\sigma T_{sky}^4) + (1-F)(\epsilon\sigma T_s^4 - T^4) \quad (C-3)$$

$$Q = \frac{1}{R} (T_i - T_s) \quad (C-4)$$

where Q = heat loss in Watts/m²

hc = convective heat transfer coefficient

T_s = roof surface temperature

ϵ = broadband emissivity of roof surface

T_a = ambient air temperature

T_{sky} = skydome apparent temperature

T_b = apparent temperature at the roof of objects which block the roof from being the entire skydome hemisphere

F = skydome fraction at the roof

$1 - F$ = background fraction of the roof

σ = Stefan-Boltzmann constant

R = thermal resistivity of the structure from inside surface to outside surface

T_{inside} = inside temperature of the structure

Given all parameters except Q and T_{inside} , there is a unique solution of Q and T_{inside} which can be done by iteration. Therefore, with a given scenario including meteorological conditions, R-factor, building configuration and roof material type, two things are possible. One, any of the fixed factors may be varied to determine the effect the variation has on temperature ($T_{surface}$) and on heat loss (Q). Some of the parameters which have been varied include emissivity, skydome function and resistivity (R)*. Second, an error analysis may be done on the various parameters with relationship to either $T_{surface}$ or Q .

* Some examples of this program's output can be seen in Figure C.5-1.

A summary of the relevant programs can be seen in Table C.5-1

TABLE C.1-1
LOCATION AND DESCRIPTION OF W-T
TRANSFORMATION RELATED DATA FILES

<u>TAPE NAME</u>	<u>FILE #</u>	<u>FILE SIZE</u>	<u>DESCRIPTION</u>
Emissivity #1	5	[41,5]	70-150 deg K, every 2 deg (even degrees) [T deg K, D3 μ m, D5 μ m, D8 μ m, D14 μ m]
Emissivity #1	6	[41,5]	150-230 deg K, every 2 deg (even degrees) [T deg K, D3 μ m, D5 μ m, D8 μ m, D14 μ m]
Emissivity #1	7	[44,5]	230-316 deg K, every 2 deg (even degrees) [T deg K, D3 μ m, D5 μ m, D8 μ m, D14 μ m]
Emissivity #1	11	[38,5]	241-315 deg K, every 2 deg (odd degrees) [T deg K, D3 μ m, D5 μ m, D8 μ m, D14 μ m]
Emissivity #1	2	[84,3]	150-316 deg K, every 2 deg, (even degrees) [T deg K, W ₃₋₅ , W ₈₋₁₄]
Emissivity #1	8	[42,3]	259-300 deg K, every degree [T deg K, W ₃₋₅ , W ₈₋₁₄]
Emissivity #1	12	[38,3]	241-315 deg K, every 2 deg (odd degrees) [T deg K, W ₃₋₅ , W ₈₋₁₄]
Emissivity #1	13	[26,3]	290-315 deg K, every degree [T deg K, W ₃₋₅ , W ₈₋₁₄]
Emissivity #1	15	[66,2]	150-280 deg K, every 2 deg, (even degrees) [T deg K, W ₈₋₁₄]
Emissivity #1	16	[76,2]	150-300 deg K, every 2 deg, (even degrees) [T deg K, W ₈₋₁₄]
Emissivity #1	9	[76,2]	200-350 deg K, every 2 deg, (even degrees) [T deg K, W ₁₋₂₀]
Heat Loss #1	3	[44,2]	230-316 deg, every 2 deg, (even degrees) [T deg K, W ₈₋₁₄]
Heat Loss #1	12	[36,2]	260-330 deg, every 2 deg, (even degrees) [T deg K, W ₈₋₁₄]
Thermal Calibration	3	[44,2]	230-316 deg K, every 2 degrees (even degrees) [T deg K, W ₈₋₁₄]
Thermal Calibration	4	[44,2]	230-316 deg K, every 2 degrees (even degrees) [T deg K, W ₃₋₅]

TABLE C.1-2
THERMAL CALIBRATION TAPE

KEY #	INPUTS	OUTPUTS	DESCRIPTION
F0	Flight date, gain, blackbody, data, wedge densities	Table of volt-density temp. deg C for each step	Using the blackbody density and temperature, gain and wedges densities, set up a volt-density temperature conversion; stores the information in an[11,3] matrix
F1	File of stepwedge, bandpass, change in blackbody or gain	Date, blackbody information and gain	Loads the step wedge from a computer file, allows for any change in blackbody density or temperature and gain, recomputes the density to temperature conversion in case of change and identifies the wedge.
F2	Gives the lowest and highest T in wedge; input T (min), T(max) and T(Tic)	Plots of volts vs. density and density vs. temperature	Using the wedge loaded with key F1, outputs the plots.
F3	Point #1 altitude density, angle	Point #, altitude, temperature (deg C) angle	Given the stepwedge and the density, outputs the apparent temperature at altitude and angle
F4	Altitude: Min, Max, Tic; Temperature: Min, Max, Tic; No. of points and altitudes; altitude, temperature for each point	A plot of temperature vs. altitude for N points at M altitude	Plots the altitude versus temperature profiles for any number of points to aid in visual extrapolation to T(0,0)
F5	Number of points, T(altitude) read, T(0,0) extrapolated	WA (H,0) Tau (H,0)	Performs a regression analysis according to the profile calibration technique to obtain WA and τ

THERMAL CALIBRATION TAPE

KEY #	INPUTS	OUTPUTS	DESCRIPTION
F6	Number of points; T(H,0), T(H,Θ): T _{sky} , WA, τ	T _{sky} , W _{sky} , T(H,0), T(H,Θ); T', T-T'	Performs a manual iteration for W _{sky} for minimum T-T', where T is T(actual) and T' is T(actual) taken from vertical and angular viewing respectively.
F7	↑, WA, W _{sky} , object number, density, falloff (inches)	Temperature	Using the scanner calibration, stepwedge, atmospheric calibration and emissivity, calculates the temperature of any object from the film density.

TABLE C.2-1
BI BAND RATIOING TAPE

PROGRAMS

File #	Description
1	Takes The density and falloff of roof readings from a file converts to apparent temperature and radiance, corrects for atmospheric and angular effects, and stores results.
2	Loads The result of the above program, plots the relative radiance ratios, and outputs the mean and standard deviation for the ratios from each classification group.

DATA

File #	Data Dimensions	Data Description
5	[92,6]	Commercial roofs - ID #, Material Type 8-14 μ m density, falloff, 3-5 μ m density, falloff
6	[58,6]	Residential roofs - ID #, Material type, 8-14 μ m density, falloff, 3-5 μ m, density, falloff
4	[150,4]	Result of Program #1 - All roofs - ID #, material type, 8-14 μ m radiance, 3-5 μ m radiance
8	[11,3]	Step wedge for imagery

TABLE C.4-1
 ERROR ANALYSIS FOR
 TEMPERATURE MEASUREMENT - HEAT LOSS TAPE #1

FILE #	DESCRIPTION
7	Error analysis for temperature measurements of flat roofs- input the values of emissivity, tau, apparent temperature, WA, sky temperature, and the accuracies in percent, the output is the error in temperature space due to each variable, the probable maximum error, and the true temperature
11	Error analysis for temperature measurements of sloped roofs input as above plus skydome fraction, background temperature and the accuracies in percent, and the output is the same as above

TABLE C.5-1

PROGRAMS RELEVANT TO HEAT LOSS MODELING

TAPE	FILE #	DESCRIPTION
Heat Loss 1	2	Solves by iteration the two heat loss equations simultaneously for T surface and Q, varying one of the parameters
Heat Loss 1	0	Solves for the errors associated in temperature with both heat loss equations with respect to all parameters
Heat Loss 1	4	Plots temperature versus a parameter according to heat loss equations
Heat Loss 1	6	For varying house configurations determines and outputs F in table form.
Heat Loss 2	0	Does an error analysis on the combined Heat Loss model for temperature with respect to any of the parameters

WIND SPEED = 3 MPH
 AMBIENT TEMPERATURE = 7 DEG C
 SKY TEMPERATURE = 260 DEG K
 INSIDE TEMPERATURE = 20 DEG C
 SKYDOME FRACTION = 0.85

	R4		R11		R30	
EMISS	T(SURF)	Q(W/M^2)	T(SURF)	Q(W/M^2)	T(SURF)	Q(W/M^2)
0.84	4.23	22.37	3.31	8.61	2.95	3.23
0.86	4.16	22.48	3.24	8.65	2.88	3.24
0.88	4.08	22.58	3.16	8.69	2.80	3.25
0.90	4.01	22.69	3.09	8.72	2.73	3.27
0.92	3.94	22.79	3.02	8.76	2.66	3.28
0.94	3.86	22.89	2.95	8.80	2.59	3.29

FIGURE C.5-1 HEAT LOSS MODEL OUTPUT

References

Barr, Goodnight, Sall & Helevig, "A Users Guide to SAS," SAS Institute Inc., 1979

McPhee, K., ed. "ASHRAE - Handbook of Fundamentals," ASHRAE 1972

Pivovonsky and Nagel, 1961. "Tables of Blackbody Radiation Functions," Macmillan Company

APPENDIX D

DATA PROCESSING IN INFRARED SCANNERS

D.1 Signal Processing in the Infrared Scanner

A thermal scanner is a device which is used to create an image of the radiant energy reaching it from the ground. Scanners use photon detectors which essentially count the number of photons absorbed. As a result, they have threshold values below which they do not respond. This means the energy per photon must be large enough to exceed the scanner threshold. In general, the shorter the wavelength (the higher the energy), the better the response. The photon detector, because of the low energies it is required to detect, must be cooled well below ambient conditions to minimize detector noise. This prevents the detector from seeing its own background instead of, or in addition to, the source. The advantage to this type of detector is its fast response time and ability to respond to low signal levels.

The detector's output is a video signal with voltage level proportional to apparent temperature, i.e., to the amount of energy received. The video signal is amplified and fed into a roll compensation unit. From the roll comp unit, the video signal is used to modulate the intensity of a glow modulator tube whose output is projected back onto a scanning mirror. As the mirror scans 120°, the scan line is "painted" on the film. As both the aircraft and film advance, the next line is painted on immediately adjacent to the first until an image is formed whose film density is a function of apparent temperature (cf. Figure D-1). The roll compensation unit serves to delay or advance the video signal relative to the mirror position such that aircraft roll effects are removed from the image.

Scanning systems produce an image of the area beneath an aircraft. This process is best understood by considering Figure D-2. The scanning mirror collects information over 120° as it rotates. It directs the signal into the Cassegrain telescope where it is focused on the detector. The size of the detector and the focal length of the collection optics define the instantaneous field of view of the scanner. This, together with flying height, defines the resolution or spot size of the scanner on the ground.

The internal scanner calibration can be accomplished by permitting the detector to view one or more blackbody cavities as it scans through the 240° not used in viewing the ground.

The main advantages of a scanner are spatial resolution, the image formed, and its sensitivity to small temperature differences. For the Bendix LN-3 scanner used in this study, the instantaneous field of view is 2.5 milliradians with sensitivity of a few tenths of a °C.

Radiometric calibration of the sensing system is performed on a periodic basis to ensure internal system accuracies and to provide a definition of the sensor's response functions.

Calibration of the scanner response function is a somewhat difficult and time-consuming process. Initial calibration involves use of a step wedge to define the relation between the density measured on the film and the voltage from the detector. This response curve is generated in operational situations for each v/H (film transport speed) setting and at regular intervals if v/H remains constant.* An example of such a curve is shown in Figure D-3. This curve is a function of film processing and v/H setting. Sensor linearity is then checked by letting the scanner view water baths at various temperatures at fixed gain and DC level settings. By converting the recorded film densities to voltages using the step wedge data and plotting voltage versus temperature, the detector linearity can be checked. Figure D-4 illustrates such a system linearity check.

The system gain is defined as the change in voltage associated with a unit change in temperature. This is controlled by the operator and the gain controls are periodically calibrated. This is done by permitting the scanner to view two water baths at different fixed temperatures. The density associated with the baths are converted to voltage and the change in voltage over the change in bath temperature are plotted against gain setting for the range in gain settings used in operation. Figure D-5 illustrates the results of this type of

* v = Velocity of aircraft

H = Altitude of aircraft

calibration.

The final step is to calibrate the blackbody temperature. The scanner is allowed to view two temperature controlled standards and the blackbody. The associated film densities are then converted to voltage using the associated density-voltage curve. Since the system temperature response is linear with voltage and since two temperatures are known, it is possible to calculate the internal blackbody temperature.* The complete blackbody calibration is accomplished by plotting the control setting versus calculated temperature for the range of temperatures of interest (as shown in Figure D-6).

Internal scanner calibration can then be accomplished by use of the density-voltage curve to obtain output voltages, the change in voltage over temperature-gain curve to obtain the slope of the scanner response function and the blackbody curve to find the intercept of the response curve,

i.e.,
$$V = \frac{\Delta V}{\Delta T} (T - T_{bb}) + V_{bb} \quad (D-1)$$

where

V is voltage

$\frac{\Delta V}{\Delta T}$ is determined by the gain setting, and

T is temperature

where V_{bb} and T_{bb} are the voltage and temperature associated with the blackbody.

D.2 Thermogram Geometry

One of the major problems with scanner systems is the geometric distortion in the imagery produced. The three major sources of distortion are tangent error, roll and v/H distortion.

The tangent error results from the film being curved when the image is "painted" on. The curved film is used to keep the glow modulator tube focused on the film over the entire 120° scan. The tangent effect is illustrated in Figure D-7.

* For precise calibration, corrections for emissivity must be made for all reference surfaces and the blackbody.

The error from aircraft roll was discussed briefly in Section 2.A.2. It is introduced by roll in the aircraft changing the area viewed by a scan and is illustrated in Figure D-8 which shows a string of barges in the Hudson River which should appear in a straight line.

Aircraft pitch and yaw can also introduce geometric errors, but these are usually small and can be minimized by proper collection procedures.

The third major source of error is from improper v/H settings. This is the ratio of aircraft speed over altitude which controls the rate at which the film is transported. The errors result in the scan lines being too closely spaced or too far apart. This results in a one-directional stretch effect in the image as shown in Figure D-9.

The combination of these three effects can produce a badly distorted image. The removal of error due to roll was discussed in Section 2.A-1. The v/H and tangent errors can be removed by displaying the image on a black and white cathode ray tube (CRT). In the display process, the vertical sweep signal has a series of stepped corrections applied to it which stretch out the signal and remove the tangent error. It is also possible to apply a linear correction to the vertical and horizontal sweep which permits scaling of the image. Because these controls are independent, the horizontal axis can be stretched or compressed more than the vertical to compensate for the v/H error. The data can then be further scaled, if desired, by viewing the screen with a modified Zoom Transfer Scope (ZTS) and scaling it to a map base. Using this approach, the image can be corrected and scaled to a map base. For certain applications, where correct geometry is not necessary, the original imagery (usually in enlarged form) can be directly displayed for interpretation.

FIGURE D-1 THERMAL SCANNING PROCEDURE (after HRB Singer).
 (a) Scanline Pattern Below Aircraft.
 (b) Detector Signal Along a Single Scan Line.

FIGURE D-2 INFRARED SCANNER DESIGN

D-7

FIGURE D-3 FILM-DENSITY VS. SCANNER OUTPUT

D-8

FIGURE D-4 DETECTOR OUTPUT VOLTAGE VS. TEMP

FIGURE D-5 I.R. SCANNER GAIN VS. TEMPERATURE (°C)/VOLT

FIGURE D-6 I.R. SCANNER GAIN VS. TEMPERATURE (°C)/VOLT

FIGURE D-7 COMPARISON OF TARGET AND IR SCANNER IMAGE SHOWING DISTORTIONS DUE TO TANGENT ERRORS.

FIGURE D-8 IMAGERY TAKEN OVER DANSKAMMER POINT STATION
SHOWING DISTORTIONS DUE TO ABSENCE OF ROLL
COMPENSATION

The string of barges in the lower portion of the frame should appear as a straight line in properly compensated imagery.

FIGURE D-9 DISTORTIONS RESULTING FROM VARIATIONS IN THE v/H RATIO

APPENDIX E
STATEMENT OF WORK

The following is a description of the statement of work for the NYSERDA/USDOE Heat Loss Program, Calspan Project No. 295-100:

TASK 1

"The Contractor will submit a detailed project plan for review and approval by DOE and NYSERDA. This plan shall indicate, in more detail than the proposal program plan, final allocation of financial and personnel resources, timing of principal events that are to occur during execution of the project, decision points and progress milestones, technical approach, and other items of direct relevance to timely and successful accomplishment of the project objectives."

This document is intended to satisfy the requirements of TASK 1.

TASK 2

"The Contractor shall organize and participate in the activities of a Steering Committee consisting of representatives from DOE, NYSERDA, the Calspan Project Engineer and representatives of New York State utilities."

TASK 3

"The Contractor shall identify and develop laboratory and field techniques necessary to determine emissivity values of materials."

TASK 3.1

"The emittance of common building materials will be determined and a library of emittance values established. This library shall be adequately sized to evaluate the two methods proposed for determining true surface temperatures of structures included in existing field data."

TASK 3.2

"The variability of emissivity with angle, moisture and surface conditions will be studied for common building materials and incorporated as appropriate into the library. In particular, the emissivity for common roofing materials and wall coverings will be determined at various angles including, but not restricted to, angles most commonly encountered in field studies."

TASK 4

"The Contractor shall use existing imagery of the aerial survey of Syracuse University to evaluate the feasibility of the Bi-Band Ratioing method and the Photometric Material Identification method to determine emissivities."

TASK 4.1

"Evaluation of the Bi-Band Ratioing method. This method requires laboratory emissivity measurements of materials in the 3-5 μm and the 8-14 μm infrared bands and radiation measurements of field structures in the same two bands. The ratio of emissivities determined by this method permits the determination of materials."

TASK 4.2

"Evaluation of the Photometric Materials Identification method. This method requires laboratory measurements of material reflectivity in the visible portion of the spectrum as well as emissivity measurement in the 8-14 μm infrared band. The data can be used to identify materials."

TASK 4.3

"The contractor shall present to the Steering Committee his recommendations regarding the method(s) to be evaluated under Task 5."

The results obtained during Task 4.1 and 4.2 will be presented at the third meeting of the Steering Committee and recommendation for how best to proceed to Task 5 will be presented.

TASK 5

"Demonstration of applicability of method(s) approved by Steering Committee. This demonstration shall consist of the determination of surface emissivities for not less than 10 buildings from the Syracuse University data."

TASK 6

"A final report shall be delivered. This report shall include the following and shall be submitted in accordance with the instructions provided under Appendix D of the contract:

- (a) A library of emissivities for common building materials that includes:
 - (i) emissivities for at least 20 materials
 - (ii) useful results on effects of material aging
 - (iii) useful results on the variation of emissivity with angle.
- (b) A summary of the methods evaluated in Task 4, results of the demonstration in Task 5 and conclusions concerning the usefulness of these methods.
- (c) An assessment of the degree of accuracy necessary for values of surface emissivity in determining true surface temperature.
- (d) An error analysis of the parameters involved in determining true surface temperatures by aerial thermography.
- (e) Recommendations for continuing this work to a Methods Application Phase."