THE PRINCIPLES OF BUILDING SCIENCE AND THERMOGRAPHY NEEDED TO DIAGNOSE THE PERFORMANCE OF BUILDING ENCLOSURES

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ABSTRACT

Effective preventive maintenance can be applied to buildings, through improvements in diagnostic techniques and developments of building science knowledge.

Recent developments in the field of thermography demonstrate that an infrared camera operator, with expertise in building science, can accurately interpret thermal images. The application of thermography is the technique used to produce heat pictures from invisible radiant energy. The objective, at all levels of thermography, is to assess the thermal efficiency of building enclosures by measuring the varying levels of thermal radiation. At present, building science knowledge is not being applied to identify problems correctly, or to recommend and implement remedial measures. Thermography contributes to the effective application of this knowledge. The biggest dollar savings from Energy Efficiency programs comes from preventing enclosure degradation in the short term, and energy savings through improved efficiency of the enclosure in the long term.

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1. INTRODUCTION

Public Works Canada (PWC) recognizes the responsibility of all building owners to improve the energy efficiency of buildings. As such, PWC is committed to improve the energy efficient performance of its buildings and has sponsored, from its own budget, many technological development projects (Thermography, Purchase and Use of Solar Heating - PUSH, Program of Assistance to Solar Equipment Manufacturers PASEM) to acquire preliminary knowledge and develop the necessary expertise to achieve energy efficient building.

Recent developments in the field of thermography demonstrate that an infrared camera operator, who has been trained in building science, can accurately interpret thermal images to give an instant assessment of the actual thermal performance of buildings. The ability to make this assessment (on-site or in a lab equipped for video playback, depending upon the complexity of the problem) is a basis for an accurate prediction of the overall performance of an enclosure system in the field. This capability of real-time evaluation improves retrofit, and encourages innovative design and construction assemblies.

Public Works Canada (PWC) has expanded the term thermography into a generic statement, covering various applications and levels of infrared (IR) technology, in diagnosing the performance of building enclosures. Basic to all applications, is the technique for producing "heat pictures" from the invisible radiant energy, which all objects emit, as well as the expertise in building science needed to interpret the images. All objects, by virtue of their temperatures, emit electromagnetic radiation in the wavelength range of 0.1 um to 100 um, as thermal radiation. The objective of all levels of thermography is to assess the thermal efficiency of building enclosures by measuring the varying levels of thermal radiation. This result is obtained by identifying and recording surface heat loss characteristics and by locating surface temperature anomalies using an IR camera. As well, the significance of these findings is interpreted applying building science analysis to the construction to identify the mechanisms which cause them. Public Works Canada defines the levels of application of IR technology as follows:

<u>Level 1 Thermographic</u>. Locating thermal anomalies and interpreting problem mechanisms. Both activities are performed by a para-professional (Thermographer, a trained IR camera operator with a para-professional knowledge level of building science) and produce qualitative results.

<u>Level 2 Thermologic</u>. Interpreting the significance of the identified problem mechanisms to the construction, and recommending appropriate action to correct the problem. Both activities are performed by a Thermologist (a trained IR camera operator with a professional knowledge level of building science) and produce quantitative results.

<u>Level 3 Building Science</u>. Interpreting the cause and effect of building problems and detailing design recommendations to correct existing complex problems and prevent future occurrences. All activities are performed by a Building Scientist (a trained IR thermal image interpreter with a specialist knowledge level of building science) and produce quantitative results.

A fundamental knowledge of building science (refer to Glossary) is required for all levels of thermography. Without this knowledge, the correct interpretation of a building anomaly from an IR thermal image, cannot be assured.

Owing to the relative newness of building thermography, Public Works Canada (PWC) developed a generic methodology to organize IR diagnosis of building construction. This methodology is discussed in Section 3. The recently established Canadian Infrared Thermographic Association (CIRTA) will offer thermographic training until universities and technical colleges have adequate courses. CIRTA will use the Public Works Canada training program which assists in guaranteeing the quality of national thermographic practices and ensures that the technology of thermography is transferred to the private sector at an acceptable level of competence.

1.1 Development of Public Works Canada Capability in Thermographic and Thermologic Diagnosis of Building Envelope Deficiencies

Since September 1978, Public Works Canada has been leading a Canadian Government project involving the Public Works Canada Headquarters and some Regions, Department of National Defence, National Research Council, and Department of Indian and Northern Affairs. The objective of this project is to establish the potential of thermography for the evaluation of building enclosures in the diverse climates of Canada.

Our investigation of building enclosure systems, with the aid of thermography, allows us to conclude that:

(1) A knowledge base, emphasizing how enclosures perform rather than precisely how they are built, encourages new ideas in enclosure design.

(2) Thermographic qualitative and quantitative results can add to the knowledge base, and can be measured when a minimum 10°C (18°F) temperature drop across any component exists, and the exterior temperature is +5°C (41°F) or below. Standard roof surveys are not restricted to this temperature difference since problem detection with IR relies on solar radiation to warm up the saturated roof sandwich. Consequently, high exterior surface temperatures are of benefit prior to implementation of the survey.

(3) The use of building science investigation procedures, in conjunction with thermography equipment, reduces inaccuracies in the measurements of material surface temperatures. The inaccuracies in measurements may be caused by the varying thermal conditions across the wall due to the daily effects of the environment.

(4) Air movement at material surfaces and interstitial spaces of a wall system, contributes significantly to surface thermal expressions. Interstitial and surface convection is a primary mechanism affecting the thermal radiation at a wall's surface. Using thermography, the net results provide thermal patterns of a building enclosure's performance, derived from quantified surface temperature variations. These effects are influenced by seven types of heat transfer caused by air movement.

Recent analysis of the actual life-cycle costs, for new and existing commercial and residential buildings, shows that the maintenance cost is often the most expensive factor in owning and operating a building. Effective preventive maintenance can be applied to buildings, through improvements in the diagnostic techniques and developments of building science knowledge. In many instances, the biggest dollar savings from the Energy Efficiency programs comes from preventing enclosure degradation in the short term, and energy savings through improved efficiency of the enclosure in the long term. Generally speaking, good building science knowledge is not being applied to identify problems correctly, or to recommend and implement remedial measures. Consequently, the high overall energy efficiency of existing building enclosures is not being attained, for winter heating or summer cooling cycles.

The awareness of our limited supplies of energy, and the increasing dollar cost of that energy has highlighted the need to improve building enclosure design with emphasis on energy efficiency.

Laboratory tests designed by the Architectural Sciences Division of PWC were related to our findings from field investigations. The purpose of the tests was to identify the mechanisms leading to failure of wall assemblies. This was achieved by designing deliberate faults into the lab test wall which would demonstrate a particular mechanism (e.g.: convection, conduction, etc.) (Figure 1.) In the process of testing material use and wall assembly performance, it became evident that many established construction practices are inadequate to meet the current energy efficiency requirements. For example, the practice of applying sealant to exterior surfaces as a primary air seal is not effective owing to physical stress on the material, primarily caused by weather fluctuation.

Other questionable practices leading to air seal and vapour barrier discontinuity are: inserting prefabricated components in precast construction with inadequate consideration of either a joint detail in 3 dimensions or dimensional tolerance of materials in response to the daily effects of the environment; structural steel frame penetrating masonry walls; no tolerance in material assembly to account for dimensional change due to chemical or thermal properties (e.g., shrinkage of concrete block; use of materials with incompatible coefficients of thermal expansion - metal and brick); and inadequate detailing at the fluted edge of pressed-steel roofing decks. All of these practices can waste energy in the long term (50 years) and, more significantly can create excessive costs in the short term (5 years) due to accelerated degradation of certain building materials.

Our laboratory results demonstrate that the most common causes of thermal deficiencies of the building enclosure system are: insulation omission and discontinuity; displaced insulation; insulation deficiency (saturated, squashed, short .....); air seal failure or discontinuity and vapour barrier failure or discontinuity. With thermography, we can successfully detect these five generic deficiencies, as well as the various sub-expressions of resulting thermal inadequacies. The most significant sub-expressions relate to the seven types of heat transfer due to convection. This has a great effect on the thermal efficiency and the surface temperature measurement of walls.

It should be noted that these lab tests were performed using thermal imaging and non-imaging equipment. A trained IR camera operator with an understanding of building science is required to work this equipment properly.

1.2 The Building Enclosure Science and Technology Program (BEST)

To reduce the present demand for energy by the year 1990, we must improve the performance of our existing building stock, in particular that of the building enclosure system. The existing Canadian building stock consumes approximately 2.3×10^{14} BTUs per year[5]. The expected projections for new buildings constructed by 1990, are an additional 5.5×10^{14} BTUs per year. This approximate figure is based on the assumption that all new buildings will meet the Canadian energy requirements. In existing buildings, it is a possibility to reduce energy consumption by 11.3×10^{14} BTUs per year. In new buildings, the corresponding figures are 3.8×10^{14} BTUs by 1990. These figures clearly suggest that substantial benefit will be derived from improved diagnostic procedures, and a greater knowledge of actual building performance. The program discussed in the following paragraphs is designed to assist in achieving this benefit, and to develop diagnostic techniques and procedures for evaluating existing building enclosures. These techniques and procedures are aimed at realizing new knowledge for low energy consuming building designs of commercial and residential buildings, in the diverse Canadian climate.

The new three-year program presents an opportunity to attract graduate students, university researchers and other government department's mid-career professionals for suitable training or retraining. The aim of this program is to develop building enclosure diagnostic experts and building design advisors. There is a dearth of such expertise in government, private sector and schools; this expertise is, however, necessary for the appropriate implementation of diagnostic technologies into the building industry.

The current Public Works Canada program on Building Enclosure Science and Technology involves interdepartmental, private sector and regional participation. The program will use longwave and shortwave infrared (IR) equipment, ground and aerial thermographic data and computer facilities. The aim of this program is to further develop diagnostic procedures during 1980-82 fiscal period for the following applications:

1. To assist in quality evaluation of new buildings, by identifying and thus providing an understanding of actual thermal performance while the building is under guarantee.

   (This includes the insulation assessment in the building enclosure to reduce heat loss; the effectiveness of the air/vapour barrier to control air and vapour flow; the siting and design of the building enclosure to maximize desired heat gain; and the matching of the heat loss and heat gain characteristics of the building enclosure with the thermal capacity of the building.)

2. To establish thermography as an effective preventive maintenance tool.

3. To assess and quantify the energy efficiency of building enclosures by interpreting heat flux distribution through the building (for retrofit purposes and passive energy utilization).

4. To improve building science expertise and practices in design and construction.

Without the support of building science expertise, correct interpretation of a building's anomaly from an IR thermal image is not assured. Energy analysis of building enclosures is a relatively new and expanding field. Few people in government or the private sector are properly trained for such work. Before the appropriate energy science analysis of building enclosures can be applied on any scale, a strong emphasis must be placed on the adequate training of people. Therefore, Public Works Canada has developed training programs to transfer thermographic and thermologic procedures to the Building Industry. These thermographic programs are practical, efficient and highly desirable for the private sector.

The recently established Canadian Infrared Thermographic Association (CIRTA) assists in guaranteeing the quality of national thermographic practices. Until universities and technical colleges can provide adequate training, CIRTA will utilize the Public Works Canada training program. Our methods ensure that the technology of thermography is transferred to the private sector at an acceptable level of competence.

2. PERFORMANCE PRINCIPLES TO BE CONSIDERED BEFORE INVESTIGATING A BUILDING

2.1 Building Enclosure Performance Principles

In this age of energy shortages, building enclosures must maintain effectively and efficiently the desired interior environment. A building enclosure should provide a thermal barrier to ensure an environment within a limited tolerance ($\pm 2°C$) despite seasonal and daily fluctuations of the exterior environment.

There is a benefit/cost relationship between the thermal efficiency of enclosures, fuel consumption, and size of the heating/cooling plant. A potential saving of 6.1×10^{14} BTUs per year exists in existing residential buildings. In commercial buildings, it is possible to reduce the energy demand by more than half, saving approximately 5.2×10^{14} BTUs per year. In both instances, an efficient building enclosure is a paramount requirement for achieving this benefit. If the building enclosure meets its designed thermal resistances, then the interior environment retains efficiently the heat put into it by the mechanical systems, and thus, less fuel is consumed in heating the building. If the heating services are working efficiently, then the heat loss through an inefficient enclosure becomes more significant for energy conservation priorities.

Thermography is a diagnostic tool that allows the quick and efficient quality appraisal of enclosures towards improving energy efficient practices of insulation, and air seals in current design and construction. For example, great benefits can be gained by controlling the single factor of air leakage across a wall. The ratio of energy lost through air leakage to the total energy consumed by a building ranges between 20-30% and as high as 50%.[10]

The amount of heat lost from the high energy source inside a building, when the lower energy field is the exterior environment, is governed by a combination of five heat-transfer mechanisms. These are: conduction, convection, radiation, air flow and the phase change of water. Traditionally, only conduction, convection and radiation are considered influential in the thermal performance of buildings. However, our laboratory tests demonstrate that interstitial convection initiates subsequent air movement causing significant heat transfer. Also, when interior air is leaking to cold exterior surfaces, the phase change of vapour to water within the interstitial space of a wall, noticeably affects the surface temperatures of certain porous materials. This effect enables thermography to detect the presence of moisture and to locate areas of probable degradation.

Our studies lead us to conclude that surface and interstitial air movement have a greater overall significance for a wall's thermal efficiency than other mechanisms tested (i.e. conduction, radiation, air flow and the phase change of water); convection is a primary mechanism influencing heat transfer via the following seven types of air movement:

(1) Exterior Contact. Exterior air to exterior material surface.

(2) Exterior Open Loop. Exterior air passing through interstices in materials and structure and back to outside.

(3) Infiltration. Exterior air passing through materials and structure to interior spaces.

(4) Closed Loop. Circulation of air within a closed system (often the insulation) between warm and cool surfaces.

(5) Exfiltration. Interior air passing through materials and structure to the exterior.

(6) Interior Open Loop. Interior air passing through interstices in material to air barrier within the wall and returning to the inside.

(7) Interior Contact. Interior air to interior surface.

An understanding of these environmental effects, as well as one-dimensional steady-state heat transfer(9) and temperature-index calculations(7)(8) are invaluable to the building industry for assuring the correct interpretation of any thermogram representing the thermal performance of building enclosure.

Energy evaluation tools, such as thermography, can also be used to teach the principles of heat transfer and of physics and chemistry applicable to building enclosure systems. Because material degradation begins at the molecular level, an understanding of physics and especially chemistry is invaluable. Often, insufficient control of some physical or chemical process results in an inadequate performance of the material or assembly of materials. The sophisticated tool of thermography can provide insight into building enclosure problems, which required a high expertise in building science to identify.

2.2 IR Equipment Performance Principles

Infrared scanning devices are non-contact indicators of apparent surface temperature. This characteristic makes an IR system more effective than a surface thermocouple, because the measurement device is not in contact with the object under study, and does not influence the surface temperature.

When attempting to thermally define the area of a wall, it is preferable to collect surface temperature data from numerous locations, to statistically substantiate the results. The length of time taken to record data, by nonsimultaneous methods, may influence the relevance of the data, since the temperatures can deviate from the temperature condition of previous readings.

Recently developed thermographic devices have a response time so fast, that they assimilate almost 500 000 temperature measurements per second. These devices scan the viewed area and present the data as an image allowing holistic temperature interpretations to be made.

Because infrared scanners are non-contact, the quantity and quality of the information it receives relies upon spatial and thermal conditions. This information is influenced by three basic factors:

The Sender. Objects emit energy with a wavelength distribution and intensity dependent on their temperature and ability to emit energy. As well, objects reflect a percentage of the radiated energy from surrounding objects that strikes them as long wave radiation.

It should be noted that the emittance of a real object can be different for various thicknesses, while the emissivity remains constant. This phenomenon exists because emittance takes into account factors such as shape, orientation and thickness whereas emissivity refers only to the properties of the materials surface. Emissivity tables include objects with values in the complete IR spectrum (1-100 um). The IR windows used for building investigation operates only at select wavelengths (see section on Receiver). Consequently, emissivity values for building materials should represent the IR window used when quantifying surface temperatures. Equally important, for interpreting the actual emittance of a materials surface as represented by a thermogram, is the cumulative effect of the five heat transfer mechanisms (section 2.1, conduction, convection, radiation, air flow and the phase change of water). Accuracy of this interpretation is critical to the correct diagnosis of building performance.

Transmission Medium. The amount and characteristics of the space between the Sender (Emitter) and the Receiver (Detector) affect the perceived information. The daily effects of the environment (temperature, moisture, wind and the many subsequent effects) have an influence in this regard. This influence need not necessarily be problematic. For example, many over-cautious statements concerning the maximum wind speed for qualitative thermographic inspections unnecessarily limit the use of thermography to the building industry. Our tests show that meaningful qualitative thermographic information can be collected in a range of environmental conditions provided that the camera operator has sufficient understanding of building science and of the daily effects of the environment.

For quantitative results, greater knowledge is needed about the cumulative interrelated effects of the following factors: the presence and state of H_2O; material roughness; pollutants; reflected radiation; and angle of view of the scanner. Basic physics, with regard to IR radiation and related heat transfer theories, is highly significant for accurate thermogram interpretation. Since all real objects radiate less energy than a blackbody (a blackbody is the theoretical object which acts as a perfect absorber and perfect emitter of thermal radiation), particular emphasis should be given to the Stefan-Boltzmann Law, which describes emissive power of a blackbody.

Also relevant is Planck's Law which plots the distribution of a blackbody's monochromatic emissive power vs. wavelength. Simply stated, the peak monochromatic emissive power increases as temperature decreases and occurs at shorter wavelengths for higher temperatures. This inversely proportional relationship is expressed in Wien's Displacement Law and is significant to the choice of LW/SW window for various environmental conditions.

The Receiver. A wide variety of infrared detectors is now available. The most important consideration with respect to IR systems is the wavelength band at which the sensor operates. The most used systems are sensitive in the 2 to 5.6 um range. This range is referred to as the shortwave window (SW). Recently, detectors that are sensitive in the 8 to 12.6 um range, and referred to as the long wave window (LW), have become available. Any interpretation of real-object radiation, made by an IR camera, is an average of the total information received by either the longwave or the short wave window. This is important when calculating apparent surface temperature using published emissivity data because this data is derived using equipment responsive to different widths of IR windows.

Special note should be drawn to the difference in the thermal image recorded with the different IR windows, because the windows respond differently to the properties of the Sender and the Transmission Medium. For example, when using the SW window, the transmitted energy through glazed surface for surface temperature measurement varies depending on whether the operator is working from the high or low energy face of the glass (Figure 2). The presence of H_2O in the column of air is insignificant at low temperatures range - 10°C to 30°C (14°F to 86°F). However, H_2O is a critical factor in the column of air, when taking the measurements at temperatures greater than 100°C (212°F).

Similarly, when using LW IR equipment, reflections from surrounding energy sources play a more significant part in the interpretations of the apparent surface temperature. The low background temperatures experienced in exterior surveys in Canada and the generally high emittance of building materials, minimize problems related to reflected radiation. However, materials with low emittance, like glass and polished metals, reflect a large portion of incident radiation from its surroundings.

Using the SW window, the surface temperature to be measured should be greater than the temperature of the surroundings, in order to reduce the measurement error due to reflection. Common to all systems, is the ability to transfer the low energy (in comparison to the full electromagnetic wave band) IR wavelength, into an amplified signal which can be manipulated to provide the information in a usable format.

To deal with many of these measurement computations, Public Works Canada is setting up an on-line computer system that will store data from thermograms, environmental conditions and building components for synthesis. Due to complexity of relating building science data with field thermograms, computer programs will be used to interpret the requirements for low energy consumption of building enclosure designs.

Thus, supported by an understanding of building enclosure performance principles and IR equipment capabilities and limitations, thermography can be used to make a holistic and instantaneous estimation of the apparent surface temperature values. An understanding of the environmental conditions at the time of the thermographic survey, must be established before surface temperatures can be used to determine the degree of heat exchange between materials and their surrounding environment. This understanding allows effective deductions to be drawn in regard to a component's thermal diffusion, anticipated thermal stress, or probable movements. This information becomes invaluable, when one attempts to analyse or predict anomalies of wall performance based on comparative deductions between laboratory values, work experience and on-site interpretations of the building construction and technologies used.

3. GENERIC METHODOLOGY FOR BUILDING ENCLOSURE DIAGNOSIS

Since 1976, Public Works Canada has been developing a generic methodology of diagnostic techniques enclosure evaluation. This methodology allows PWC to improve preventive maintenance procedures and enclosure system designs in existing and proposed government buildings across Canada. The methodology comprises four phases of building enclosure diagnosis:

1 - Development of Problem Statement and Scope Identification.
2 - Identification of Problems and Significant Mechanisms of Failure.
3 - Problem Interpretation.
4 - Problem Requirements, Opportunities and Solutions

and relates specifically to three thermograph modes (1 - Aerial; 2 - Ground; 3 - Interior).

The knowledge requirement of each phase can be referred to in the Knowledge Level Summary, shown under Building Science Requirements, on the right hand side of the Generic Methodology Chart (Figure 3). The right-hand side of the chart shows the points needed for thermography and building science requirements. The left-hand side of the chart shows where they relate to the three modes of field operation. The relationship of the four phases of building enclosure diagnosis, to the three modes of thermography field operation is explained in sections 3.1 to 3.5. A knowledge of the fundamental principles of building science is required for all phases. The fundamentals of Building Science refer to:

A. Building Physics

1. heat transfer and radiation
2. psychrometry
3. fluid dynamics
4. structure
5. sound

6. weather and climate

B. Enclosures

Principles

1. heat transfer and buildings
2. solar radiation and buildings
3. water and buildings
4. wind and buildings
5. air leakage and buildings
6. air quality, people and buildings
7. structural stability and buildings
8. fire prevention/control and buildings
9. sound/acoustic control and buildings

10. public safety and buildings

Performance

11. people and buildings
12. enclosure elements

exterior	interior
- roofs	- walls/partitions
- walls	- floors/ceilings/ soffits
- windows	- furnishings and finishes
- foundations (building and soil)	
- soffit and other components	

Materials

13. nature of materials
14. durability of materials
15. deterioration of materials
16. strength of materials
17. combustibility and resistance (fire, thermal, acoustic)

C. Environment

Environmental Qualities

1. people and the interior environment
2. interior thermal environment
3. daylight and illumination
4. sound and building acoustic
5. air quality and composition
6. life safety and security

Environmental Services

7. HVAC
8. electrical
9. plumbing and drainage
10. vertical transportation and circulation
11. communications

3.1 Thermography Modes

Thermography investigation procedures developed by Public Works Canada consist of three modes of field operation: 1. Aerial, 2. Ground, 3. Interior (Reference to Fig. 5). One or more of these procedures may be carried out depending on the nature of building problems and the client's need. Such criteria and conditions are interpolated from Phase 1. The following is an explanation of the thermography modes:

Mode 1 Aerial. An exterior aerial survey provides sufficient thermographic data to permit a trained thermographer to make a rapid general assessment of many buildings, and to index the thermal condition of each enclosure. Areas of severe thermal discrepancy, where subsequent detailed investigations should be focused, are also identified in this survey.

Mode 2 Ground. An exterior ground survey provides more detailed investigation of the areas identified in a Mode 1 survey. Building science data can be collected at the same time, as outlined in Phase 2 and as discussed in section 3.2 (colour slides;

smoke tests; air pressures; surface contact thermocouples (interior and exterior) ambient temperatures; relative humidities (at above zero conditions); barometric pressures; wind speeds and direction; orientation; weather).

Mode 3 Interior. A detailed interior and exterior survey provides data necessary to make accurate, qualitative and quantitative assessments. Building investigation instruments (such as sling psychrometer, smoke and tracer gas tests, surface contact thermocouples (interior and exterior), air flow meter) are used and the physical conditions of the material is examined in detail.

3.2 Phase 1 - Development of Problem Statement and Identification of Scope

In this phase, the history of the building problems is collected and evaluated. The five distinct steps required to complete this phase require para-professional and professional capabilities. These steps are:

1. Request for diagnosis (owner, client, dept., etc.).
2. Collect and interpret from other's experience (reports, buildings managers, etc.).
3. Relate to contract document and Step 2.
4. Examine drawings (preferably As-Built) re: design and intent:
   - component identification, function and environment;
   - materials, chemical and physical properties, location, function, environment, specifications;
   - age;
   - contractors architect and engineers.
5. Arrange site visit with significant persons (Building Manager).

Interviews with occupants, building managers, owners and various technical personnel to verify the problems perceived in the initial request are often insightful. A review of previously written reports provides other perspectives and helps establish basic information on the causes, effects and significance of problems.

The contract documents of the building may give clues to details that may be contrary to the available building science knowledge of the period, putting the efficiency of the building enclosure in question. Through interviews, we may learn that poor performance characteristics may be more severe than recorded in many of the technical reports. This condition should always be anticipated, since reports are often based on limited site visits. Similarly, subcontractors may inform us about inclement weather encountered during construction. In many instances, this has been found to be a key to building problems, especially roof failures.

One of the purposes of compiling a problem history is to prepare the basic building data before the thermographic survey, so that the thermographer can become familiar with the performance peculiar to the building. This approach is crucial if intelligent, on-site problem identification is to be made.

3.3 Phase 2 - Identification of Problems and Significant Mechanisms of Failure (Thermographic Survey, Modes 1, 2 and 3)

To correctly interpret the mechanisms of a thermal anomaly, the information relevant to problem identification must be collected. The thirteen necessary points are identified in Phase 2, Figure 3. The Knowledge Level Summary indicates that this phase requires para-professional and professional expertise.

A sample format for thermographic data collection and derivation of surface temperature is given in Figure 4. This information is also shown on the sheets from the laboratory experiments, Figure 1.

Thermographic information and other types of data collected in the phase identifies the problems and the mechanisms of failure. The following list outlines the data to be collected.

1. Visit site alone in appropriate environmental conditions:
   a) identify phases 2 and 3, record investigator's observations on drawings,

- slides (colour),
- smoke tests,
- air pressure,
- thermographic data,
- surface temps.,
- ambient temps.,
- relative humidity,
- barometric pressure,
- wind speed and direction
- orientation,
- weather;

b) identify problem areas and interpret mechanisms of problem; open enclosures if necessary;

c) Extrapolate priority of influences, interpolate responsible factors;

2. Repeat Phase 1 activities if necessary.

The activities of Phase 1 and 2 are often repeated in cyclical fashion until the mechanism in question is isolated.

3.4 Phase 3 - Problem Interpretation (Thermologic Survey, Modes 1, 2 and 3)

In this phase, the significance of a problem, to the overall performance of a building enclosure is interpreted (Fig. 4a). It is sometimes necessary for the thermography results to be quantified and substantiated with detailed interior inspections, and subsequent building science tests. These tests are often coordinated with interior and ground thermologic surveys.

There are four distinct data collection activities in this phase:

1. Compile findings and if necessary extrapolate tests (thermologic, tracer gas, pressure panel tests, etc.).
2. Collate data into primary and secondary factors.
3. Synthesize (tests and data).
4. Develops arguments and problem interpretation: causes, effects and reasoning.

The purpose of these activities is to bring science-based knowledge and understanding into the realm of building thermography diagnosis.

To resolve the problems in a building, the root cause must be dealt with rather than with the symptoms or experiences of the problems. Providing that the problem has a thermal expression, thermography can be used to locate surface thermal expressions, their severity, or the specific source of the problem.

In many instances, the previous two phases generate questions which cannot be solved by field tests. Especially for a thermologic application, diagnostic laboratory evaluation is recommended. For example, Figure 1 shows a particular instance where the interstitial air flow effects on surface temperature distribution were detected using thermography. Note that the figure demonstrates surface temperature variations from direct effects of conduction, convection, surface air flow, and in the case of the second stud space from the right, of infiltrating exterior air.

Subsequent laboratory experiments, done under various monitored environments, were necessary to isolate and confirm this thermal pattern language. The context of other laboratory tests are similar, but they often relate specifically to building assembly problems associated with the juxtaposition of air and vapour barriers at dissimilar planes. The derived thermal patterns have great significance when determining the problem, requirements, opportunities, and solutions to be articulated in the following phase.

3.5 Phase 4 - Problem Requirements, Opportunities and Solutions (Thermologic and Building Science Surveys, Modes 1, 2 and 3)

The three activities in phase 4 enable the investigator to perform the following tasks:

1. Extrapolate problem requirements.

2. Provide alternate solutions and opportunities.
3. Select and implement retrofit.

The input from phases three and four is of paramount importance to the realization of appropriate action for the correction of a problem. Unfortunately, the tasks of these phases are seldomly implemented in the industry because phases 1 and 2 are rarely adequately done. Consequently, systematic evaluation and synthesis are essentially nonexistent. We have found this situation to be primarily due to the focus of the training institutions available to the private sector. The popular emphasis is on the tools and products associated with the construction industry rather than on fundamental knowledge. As well, the levels of expertise needed to implement these phases are of the professional and expert quality and there is a dearth of people adequately trained to qualify. In many instances, a specialist may have to be called in because of a unique material assembly, or phenomenon associated with the degradation of certain materials.

Invariably, at the completion of a diagnosis, the client prefers a one remedy solution. We have found this to be caused by the client's lack of expert knowledge of fundamental building science, thus, clients often fail to fully comprehend the broader implications of the solutions recommended. It is important to note that failure to appreciate alternatives can be catastrophic, and can interfere with recommendations. This attitude is often more detrimental to the building than the original problem. In many instances, such decisions are made for economic reasons alone, and often materials are selected on the basis of initial costs only, resulting in performances inferior to the original assembly. The balance between environment, material, and function is of key importance. When disrupted, the recommendation is often rendered inadequate, initiating a cycle of deficient building performance.

4. CONCLUSIONS

Most building enclosure problems are related to the lack of adequate understanding of building science. This can be attributed either to insufficient knowledge or to misuse of tools and skills. One should approach a building enclosure evaluation by carefully considering the influences of environment, function and material. The interrelationship between these three factors must be balanced to achieve a durable and successful building performance. Based on our findings, from our field and laboratory building investigations, this relationship is neither fully appreciated nor understood in most design and construction practices.

However, there has been considerable advance in the knowledge of building performance in the past several years. Progress has been made in the field of material science towards a better understanding of material degradation. As well, methods of evaluating thermal inadequacies resulting from lack of air and/or moisture control, in certain types of constructions, are being improved for field use.

Building designers are beginning to appreciate the importance of research dealing with different construction practices used in various climates. All actors in the building industry are now realizing the need for greater design tolerances for prefabricated components, building material shrinkage and the manufacturing process.

Based upon PWC's experience in the field of thermography, we conclude that thermography analysis has the following capabilities:

(1) it can be used to monitor the energy efficiency and to evaluate the performance of enclosure systems;

(2) it is suitable as a problem location and preventive maintenance tool, as most enclosure inadequacies have a thermal expression;

(3) it offers the means of detecting thermal anomalies, allowing a trained person to determine their causes.

The result of the greater awareness, provided through such technologies as thermography and building science, is improved future performance of building enclosure systems.

Despite the initial feeling of optimism that much needed knowledge development is being done, this effort will be of little benefit unless it is transferred and applied to working the field. Until the design and construction professions encompass building science as an integral part of the design process, the costly band-aid approach (post-occupancy problem solving) to building maintenance and energy efficient enclosure systems will continue.

5. APPENDICES

5.1 References

(1) From discussions with persons in the Cost Accounting Division of Public Works Canada (1979/80).

(2) P.A.D. Mill, "Development of PWC Capabilities in Thermographic Diagnosis of Building Envelope Deficiencies", PWC report series No. 27, 1979.

(3) P.A.D. Mill,"Thermography - A New Building Science Tool", PWC report series No. 29, 1979.

(4) Building Studies done by the Architectural Sciences Division, Public Works Canada (1978-1979).

(5) Figures and statistics released from the Department of Energy, Mines and Resources, 1980.

(6) PWC, NECP Secretariat, "Energy Statistics 1975-76 to 1977-78", March/79

(7) D.G. Stevenson, "Heat Flow Theory - Temperature Index Computations", National Research Council (NRC), Division of Building Research (DBR) 1965.

(8) D.G. Stevenson, "Heat Transfer at Building Surfaces", NRC, DBR, Canadian Building Digest #52, 1964.

(9) J.K. Latta and G.K. Garden, "Temperature Gradients through Building Envelopes", NRC, DBR, Canadian Building Digest #36, 1962.

(10) PWC, calculations from the following projects: Quebec Housing (1978-79), Rankin Inlet (1978), Fort McPherson (1978), Calgary MAPP (1978).

5.2 Acknowledgements

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5.3 Glossary

APPARENT RADIANCE - The total amount of energy per unit solid angle, per unit projected area which emanates from a surface. Thus, it includes the self-emitted radiation and the reflection due to sources other than the object of interest.

APPARENT TEMPERATURE - The temperature of an object as determined from the measured radiosity.

BLACKBODY - An ideal thermal radiator (emissivity = 1.0), which emits and absorbs the maximum theoretically available amount of thermal radiation and molecules at a given temperature.

BUILDING ENCLOSURE - The aggregate of materials and components that make up the outer shell of a building.

BUILDING PERFORMANCE EVALUATION - An investigation of the appropriateness and success of the building enclosure as a separator of interior and exterior environments.

BUILDING SCIENCE - The application of the fundamental laws and principles of physics and chemistry and their effects on building assemblies.

BUILDING SCIENCE (Level 3 application of IR technology to building investigation) - A trained IR camera operator with building science specialization (chemistry, physics, etc.) interprets specific and complex cause and effect of building problems to provide detailed design recommendations. These recommendations are for the correction of existing problems as well as avoidance of future or continued occurrences of material degradation. All activities are performed by a specialist (Building Scientist) and produce quantitative results.

BUILDING SCIENTIST - A specialist skilled in interpreting the cause and effect of building problems and in detailing designs to correct existing complex problems as well as to avoid future occurrences. The ability to do this is based upon a specialized knowledge of building science and (preferable) thermography as well.

DAILY EFFECTS OF THE ENVIRONMENT - The composite effect of temperature, moisture and air movement (including the subsequent subexpression of these factors) on building materials and assemblies. These factors are affected by the day/night and season cycles.

DETECTOR, INFRARED - A device which converts the infrared irradiance incident upon it into some other form of energy, most often electrical.

EMISSIVITY - The ratio of radiant energy emitted from a surface under measurement to that emitted from a blackbody (the perfect emitter and absorber at the same temperature). Refers only to the intrinsic properties of the material and/or its surface.

EMITTANCE, SURFACE - The ratio of radiant energy emitted from a surface under measurement to that emitted from a blackbody (the perfect emitter and absorber) at the same temperature. Differs in value from the emissivity because it relates to the properties of an object as a whole. Factors such as shape, orientation and thickness are accounted for whereas emissivity refers only to the properties of the material and/or its surface.

FUNDAMENTAL PRINCIPLES OF BUILDING SCIENCE -

A. Building Physics
1. molecules, heat and radiation
2. psychrometry
3. fluid dynamics
4. structure
5. sound
6. weather and climate

B. Enclosures

Principles
1. heat transfer and buildings
2. solar radiation and buildings
3. water on buildings
4. wind and buildings

5. air leakage and buildings
6. air quality, people and buildings
7. structural stability and buildings
8. fire prevention/control and buildings
9. sound/acoustic control and buildings
10. public safety and buildings

Performances

11. people and buildings
12. enclosure elements

exterior	interior
- roofs	- walls/partitions
- walls	- floors/ceilings/soffits
- windows	- furnishings and finishes
- foundations (building and soil)	
- soffit and other components	

Materials

13. nature of materials
14. durability of materials
15. deterioration of materials
16. strength of materials
17. combustibility and resistance (fire, thermal, acoustic)

C. Environment

Environmental Qualities

1. people and the interior environment
2. interior thermal environment
3. daylight and illumination
4. sound and building acoustic
5. air quality and composition
6. life safety and security

Environmental Services

7. HVAC
8. electrical
9. plumbing and drainage
10. vertical transportation and circulation
11. communications

HEAT TRANSFER - The movement of heat energy from a location of higher temperature to a location of lower temperature. This occurs mainly by conduction, convection and radiation, depending on the characteristics of the materials involved in the energy transfer.

HYBRID VISION - A combined thermal and visual image achieved through optical reflections via mirrors. An infrared image (thermogram) is superimposed onto the background visual of the scene under view. The two images are exactly aligned, making location of the thermal image easier to identify.

INFRARED SENSING DEVICE - A wide class of instruments used to display information which is representative of the thermal radiation from any object surfaces viewed by the instrument.

ISOTHERM - A function on certain IR equipment capable of producing a line which connects points of equal energy, representative of similar apparent surface temperatures. (From ISO - Greek for like, same and THERM - referring to the thermal infrared).

ISOTHERM THERMOGRAM - A record of a thermal image with isotherm(s) superimposed.

LEVEL (Referring to level of application of IR technology to building investigation) - Defines the degree of detailed information required to fulfill a thermographic (qualitative), thermologic (quantitative) and building science survey (qualitative specialized).

LONG WAVE - Radiation with a wavelength between 8 and 14 micrometers (the Far IR band).

MECHANISM - The process through which an existing phenomenon is realized. For example, the process(es) leading a failure or to a heat transfer.

MODE - The way or manner in which things are done. Refers to the 3 modes of field operation of thermography (aerial, ground, interior).

PHASE - Refers to the sequence of steps to be executed for building enclosure diagnosis, as defined by PWC generic methodology for building investigation.

PSYCHROMETRY - Application of the measurement of atmospheric humidity using wet and dry bulb thermometers.

STEP - A specific activity to be performed as a requirement for a phase in PWC generic methodology of building investigation.

TYPES OF AIR MOVEMENT - Refers to the circulation path travelled by a mass of air as it is influenced by the mechanism of convection.

QUALITATIVE TEST - A general (thermographic) analysis applied to determine the occurrence, type and distribution of a material or an assembly's performance.

QUANTITATIVE TEST - A particular (thermologic and building science) analysis involving a number process applied when a numerical value of a material's characteristics is required to interpret the significance of the various influences on a material or assembly's performance.

SHORT WAVE - Radiation with a wavelength between 2 and 5.6 micrometers (the middle IR band).

SURFACE EMITTANCE - The ratio of radiant energy from a surface at a given temperature to the corresponding radiant energy from a blackbody surface at the same temperature.

THERMAL ANOMALY - A thermal pattern, as sensed by an IR system, representing the characteristics of a built works which are not in accordance with the intended design performance.

THERMAL IMAGE - A visual thermal pattern representing the apparent surface temperature distribution.

THERMOGRAPHIC (Level 1 application of IR technology to building investigation) - A trained IR camera operator locates thermal anomalies and interprets the mechanisms of the problem. Both activities are performed by a para-professional (Thermographer) and produce qualitative results.

THERMOLOGIC (Level 2 application of IR technology to building investigation) - A trained IR camera operator with building science expertise interprets the significance of a problem and recommends appropriate action to correct the problem. Both activities are performed by a professional (Thermologist) and produce quantitative results.

THERMOGRAM - A two-dimensional visual record mapping a pattern language of the apparent surface temperature of the object under view. This pattern language, representing the thermal performance of the scene, must be correctly interpreted by a trained person (Thermographer, Thermologist, Building Scientist). This record may be in the format of polaroid print; 35 mm slide or negative, colour or black and white; videotape or super 8 movie film.

THERMOGRAPHER - A skilled infrared camera operator trained to produce high quality thermograms, with or without some means of temperature calibration [isotherm(s)]. A thermographer has the skill necessary to adjust all controls on the IR equipment (thermal level and range, visual brightness and contrast) to maximize the information recorded by the thermogram without misrepresenting the actual condition. A thermographer also prepares a qualitative report following a standard recording format for work completed and provides a preliminary report that records the exterior microclimate and orientation of the building, room plan indications, as well as location and direction of internal thermal imagery.

THERMOGRAPHY - A generic statement covering the various levels of application of IR technology to building investigation. Basic to all applications is the technique for producing thermal images from the invisible radiant energy emitted from objects (stationary or moving) at any distance and without influencing the temperature of the object during the measurement. Also required for diagnosis of building enclosure performance with thermography is a level of expertise in building science. All objects, by virtue of their temperatures, emit electromagnetic radiation in the wavelength range of 0.1 um to 100 um as thermal radiation. The objective of all levels of thermography is to assess the efficiency of building enclosures performance, by measuring the varying levels of thermal radiation. The significance of these findings is interpreted using building science knowledge to identify the mechanisms which cause them. The levels of application of IR technology to building investigation are defined as Thermographic, Thermologic and Building Science. A knowledge of building science is required for all levels of thermography. Without it, correct interpretation of a building anomaly from an IR thermal picture is not assured.

THERMOLOGIST - A skilled infrared camera operator competent in all the skills of a thermographer and produced a quantitative report. In addition, the thermologist had substantial knowledge of building construction, building materials, and basic knowledge of building science principles, especially those related to temperature and psychrometry. A thermologist interprets common building problems, causes, effects and devises solutions.

TRANSMITTANCE - The ratio of the radiant energy transmitted through a body to that incident upon it.

WINDOW (IR) - The term used to define the wavelength band within which an infrared detector operates. The two windows presently available are the shortwave window (SW) which is sensitive in the 2 to 5.6 um and the longwave window (LW) which is sensitive in the 8 to 12.6 um.

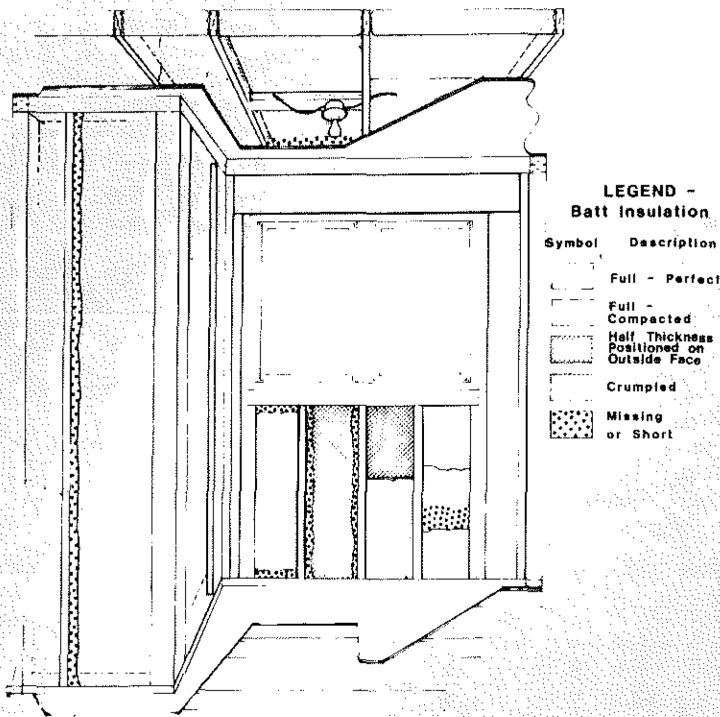


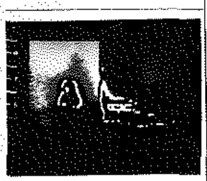
Fig. 1
(left) Drawing explaining the deliberate faults that were designed into the laboratory test wall to demonstrate particular mechanisms (e.g., conduction, convection).

(below) Samples of Emissivity and Thermogram Tests Data Sheets showing the standard data recording method and some results of the experiments.

Public Works Canada / Travaux publics Canada — EMISSIVITY AND THERMOGRAM TESTS DATA SHEET / THERMOGRAMME ET ESSAI DU POUVOIR ÉMISSIF FEUILLE DE DONNÉES — PAGE

DESIGN AND CONSTRUCTION / CONCEPTION ET CONSTRUCTION — BUILT WORKS TECHNOLOGY / TECHNOLOGIE DES OUVRAGES CONSTRUITS — ARCHITECTURE DIVISION / DIVISION DE L'ARCHITECTURE

JOB/PROJET: Wall Test — JOB NUMBER/N° DE PROJET: WT78-02



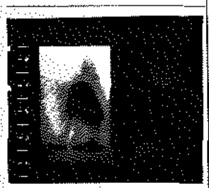
1

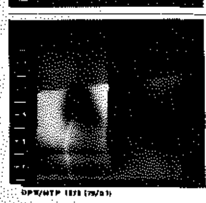
DATE	HOUR/HEURE	ROLL/PELLICULE	FRAME/CLICHÉ	LENS/OBJECTIF
78-10-29	17:15	5	25A-26A	20°

MATERIAL FINISH/FINI: Yellow Latex — REFERENCE/RÉFÉRENCE: Black Body

ENVIRONMENT / MILIEU	TEMP. CHAMBER / TEMP. CHAMBRE (Tc) (AC) -8°C	TEMP. AMBIENT / TEMP. AMBIANTE (Ta) (AC) 18°C	RH. CHAMBER / HR. CHAMBRE 98%	RH. AMBIENT / HR. AMBIANTE 34%
REFERENCE / RÉFÉRENCE	TEMPERATURE / TEMPÉRATURE (AB) 24°C	EMISSIVITY / POUVOIR ÉMISSIF (B) 1.0	ISOTHERM LEVEL / NIVEAU ISO. 1.0	
TEST PANEL / PANNEAU D'ESSAI	TEMPERATURE / TEMPÉRATURE (AD) 16°C approx.	ISOTHERM LEVEL / NIVEAU ISO. -0.1		
CAMERA / APP. PHOTO	f-STOP / NOMBRE f (AE) 1.8	DISTANCE (C) 3 m	RANGE / CHAMP 5	
COMPUTATION / CALCUL	ISO. DIFFERENCE / VARIATION ISO. 1.1	DIFF. X RANGE / VARIATION DE CHAMP X (E)	EMISSIVITY / POUVOIR ÉMISSIF (D) 0.94	

NOTES *Viewing Position #6*
Stepped
Showing air leakage and thermal bridging effects around electrical outlet and exterior corner of stud wall. Note surface temperature variation is greater than 5°C. This excessive temperature in the exterior corner is primarily due to inadequate thermal breaks.





2

DATE	HOUR/HEURE	ROLL/PELLICULE	FRAME/CLICHÉ	LENS/OBJECTIF
78-10-29	17:15	5	27A	20°

MATERIAL FINISH/FINI: Yellow Latex — REFERENCE/RÉFÉRENCE: Black Body

ENVIRONMENT / MILIEU	TEMP. CHAMBER / TEMP. CHAMBRE (Tc) (AC) -8°C	TEMP. AMBIENT / TEMP. AMBIANTE (Ta) (AC) 18°C	RH. CHAMBER / HR. CHAMBRE 98%	RH. AMBIENT / HR. AMBIANTE 34%
REFERENCE / RÉFÉRENCE	TEMPERATURE / TEMPÉRATURE (AB) 24°C	EMISSIVITY / POUVOIR ÉMISSIF (B) 1.0	ISOTHERM LEVEL / NIVEAU ISO. 1.0	
TEST PANEL / PANNEAU D'ESSAI	TEMPERATURE / TEMPÉRATURE (AD) 22°C approx.	ISOTHERM LEVEL / NIVEAU ISO. 0.70		
CAMERA / APP. PHOTO	f-STOP / NOMBRE f (AE) 1.8	DISTANCE (C) 3 m	RANGE / CHAMP 5	
COMPUTATION / CALCUL	ISO. DIFFERENCE / VARIATION ISO. -0.30	DIFF. X RANGE / VARIATION DE CHAMP X (E) -1.5	EMISSIVITY / POUVOIR ÉMISSIF (D) 0.94	

NOTES *Viewing Position #6*
Stepped and monochrome
Excellent expression of an air leakage effecting surface temperature patterns. Whisping of the dark cold thermal expression is indication of a significant air flow from the exterior cooling the surrounding interior surfaces adjacent to the air leak.

DPW/MTP 1818 (79/01)

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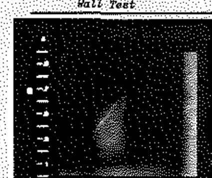
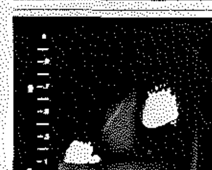
DESIGN AND CONSTRUCTION / CONCEPTION ET CONSTRUCTION — BUILT WORKS TECHNOLOGY / TECHNOLOGIE DES OUVRAGES CONSTRUITS — ARCHITECTURE DIVISION / DIVISION DE L'ARCHITECTURE

JOB/PROJET: Wall Test — JOB NUMBER/N° DE PROJET: WT78.02





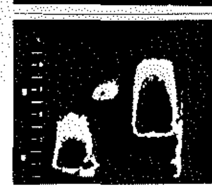
1

DATE	HOUR/HEURE	ROLL/PELLICULE	FRAME/CLICHÉ	LENS/OBJECTIF
78-10-22	23:--{23:50	3	32A-33A	20°

MATERIAL FINISH/FINI: Yellow Latex — REFERENCE/RÉFÉRENCE: Black Body

ENVIRONMENT / MILIEU	TEMP. CHAMBER / TEMP. CHAMBRE (Tc) (AC) -2°C	TEMP. AMBIENT / TEMP. AMBIANTE (Ta) (AC) 21°C	RH. CHAMBER / HR. CHAMBRE 98%	RH. AMBIENT / HR. AMBIANTE 34%
REFERENCE / RÉFÉRENCE	TEMPERATURE / TEMPÉRATURE (AB) 24°C	EMISSIVITY / POUVOIR ÉMISSIF (B) 1.0	ISOTHERM LEVEL / NIVEAU ISO. 0.70	
TEST PANEL / PANNEAU D'ESSAI	TEMPERATURE / TEMPÉRATURE (AD) 17°	ISOTHERM LEVEL / NIVEAU ISO. 0.04		
CAMERA / APP. PHOTO	f-STOP / NOMBRE f (AE) 1.8	DISTANCE (C) 3 m	RANGE / CHAMP 5	
COMPUTATION / CALCUL	ISO. DIFFERENCE / VARIATION ISO. -0.96	DIFF. X RANGE / VARIATION DE CHAMP X (E) -4.8	EMISSIVITY / POUVOIR ÉMISSIF (D) 0.94	

NOTES *Viewing Position #7*
Monochromes
Note peripheral surface temperature effects adjacent to area with no insulation still retain the uniform pattern of the area without insulation. The three expressions of surface temperature are keys to problem identification in timber construction.



ISOTHERM
ISOTHERME

2

DATE	HOUR/HEURE	ROLL/PELLICULE	FRAME/CLICHÉ	LENS/OBJECTIF
78-10-22	23:00-23:50	3	34A	20°

MATERIAL FINISH/FINI: Yellow Latex — REFERENCE/RÉFÉRENCE: Black Body

ENVIRONMENT / MILIEU	TEMP. CHAMBER / TEMP. CHAMBRE (Tc) (AC) -2°C	TEMP. AMBIENT / TEMP. AMBIANTE (Ta) (AC) 21°C	RH. CHAMBER / HR. CHAMBRE 98%	RH. AMBIENT / HR. AMBIANTE 34%
REFERENCE / RÉFÉRENCE	TEMPERATURE / TEMPÉRATURE (AB) 24°C	EMISSIVITY / POUVOIR ÉMISSIF (B) 1.0	ISOTHERM LEVEL / NIVEAU ISO. 0.70	
TEST PANEL / PANNEAU D'ESSAI	TEMPERATURE / TEMPÉRATURE (AD) 18°	ISOTHERM LEVEL / NIVEAU ISO. 1.8		
CAMERA / APP. PHOTO	f-STOP / NOMBRE f (AE) 0.18	DISTANCE (C) 3 m	RANGE / CHAMP 5	
COMPUTATION / CALCUL	ISO. DIFFERENCE / VARIATION ISO. -0.82	DIFF. X RANGE / VARIATION DE CHAMP X (E) -4.1	EMISSIVITY / POUVOIR ÉMISSIF (D) 0.94	

NOTES *Viewing Position #7*
Monochrome

DPW/MTP 1818 (79/01)

SHORT WAVE

LONG WAVE

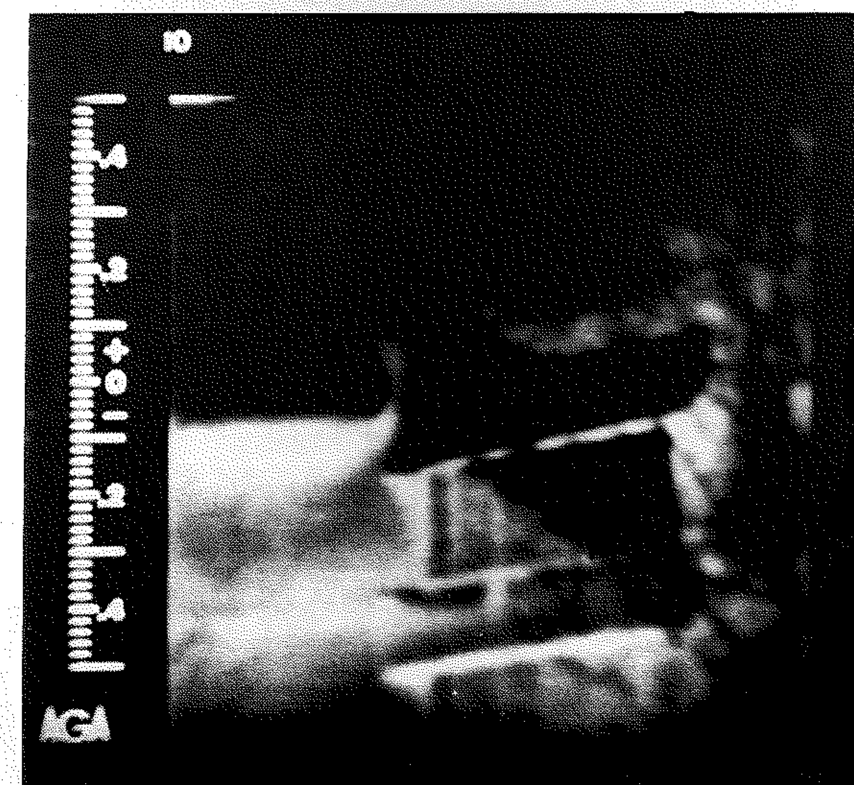


Fig. 2 Comparison of thermal images recorded by short wave and long wave windows taken under the same environmental conditions. The images demonstrate the different responses of the short wave and long wave window to the properties of the Sender and Transmission medium.
For example: 1) reflection detected from glazed surfaces in long wave vs the transmission in the short wave band; and
2) the difference in information presented providing the opportunity for greater understanding of building situation.

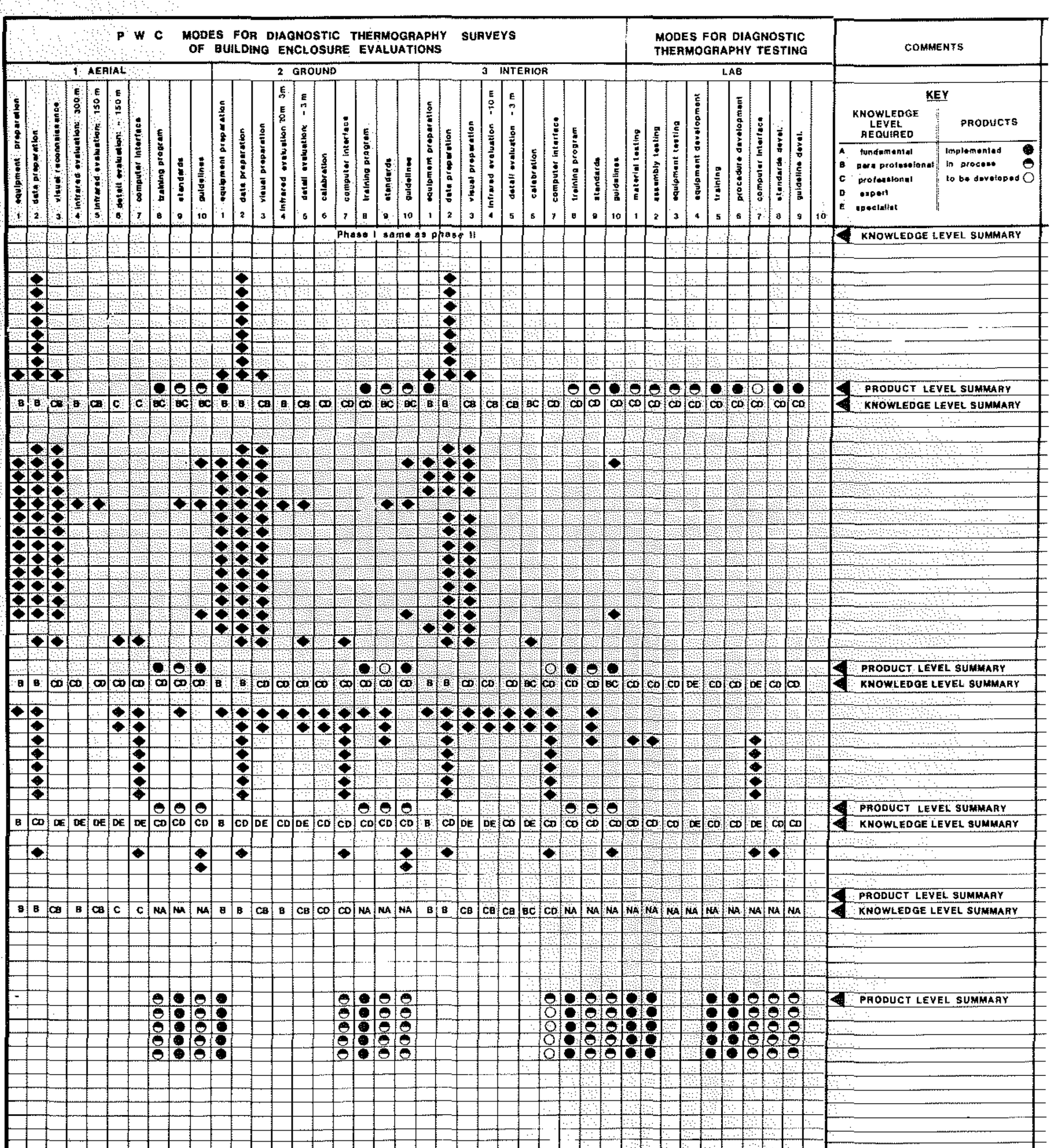


Fig. 3 Generic Methodology Chart showing the relationship of the four phases of building enclosure diagnosis to: A) the three modes of thermography and field operation (this page); and B) the thermography and building science requirements (next page)

(Continued on next page)

GENERIC METHODOLOGY FOR BUILDING ENCLOSURE DIAGNOSIS OF THERMAL EFFICIENCY

TO PROVIDE DIAGNOSTIC TECHNIQUES AND PROCEDURES
FOR EVALUATION OF EXISTING BUILDING ENCLOSURES
IN AID OF REALIZING NEW KNOWLEDGE
FOR INITIATING LOW ENERGY BUILDING DESIGN
OF COMMERCIAL AND RESIDENTIAL BUILDINGS IN ARCTIC
AND OTHER DIVERSE CANADIAN CLIMATES.

	THERMOGRAPHY REQUIREMENTS																					BUILDING SCIENCE REQUIREMENTS																		
	INFRARED IMAGING MODE										OPERATION					RECORD						PHYSICS							ENCLOSURE						ENVIRONMENT					
	monochrome	step	inverted	hybrid	isotherm	3 1/2	7	12	20	40	range	auto	manual	long wave	short wave	temperature profile	35 mm	video vtr	polaroid	oscar digital	magnetic tape mri	weather & climate	molecules, heat & radiation	radiation & environment	water in the environment	air and its water content	fluids in motion	heat transfer	building enclosures	man & the building enclosure	buildings & radiation	buildings & wind	buildings & air leakage	water on buildings	the indoor thermal environment	man & his thermal environment	daylight & illumination	sound & building acoustics	buildings & fire	buildings & public safety
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	1	2	3	4	5	6	1	2	3	4	5	6	7	1	2	3	4	5	6	1	2	3	4	5	6
PHASE I. DEVELOPMENT OF PROBLEM STATEMENT & SCOPE IDENTIFICATION																						BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC
1 Request for diagnosis(owner, client, dept. etc.)																																								
2 Collects &interprets from others experience (reports,building managers,etc.)																																								
3 Relates contract document 2																																								
4 Examines drawings re: design & intent																																								
— component identification, function & environment																																								
— materials, chemical & physical properties, location, function, environment, specs.																																								
— age																																								
— contractors architect & engineers																																								
5 If necessary arrange site visit with significant persons																																								
PHASE II IDENTIFICATION OF PROBLEMS & SIGNIFICANT MECHANISMS OF FAILURE																						BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	AB	AB	BC
1 Visit site alone in appropriate environmental conditions																																								
a Identify phases 2 & 3, record investigators observations on drawings																																								
– slides (colour)				◆	◆	◆	◆	◆	◆	◆	◆		◆	◆	◆		◆																							
– smoketests																																								
– air pressure																																								
– thermographic data	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆		◆	◆	◆	◆	◆	◆		◆	◆		◆	◆	◆	◆	◆	◆				◆
– surface temps.		◆			◆						◆	◆	◆	◆	◆	◆		◆		◆	◆																			
– ambient temps.																																								
– RH																																								
– barometric pressure																																								
– wind speeds																																								
– orientation																																								
– weather																																								
b Identify problem areas & interpret mechanisms of problem	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆																			
open enclosures if necessary																																								
c extrapolate priority of influences interpolate responsible factors		◆			◆									◆	◆	◆		◆		◆	◆																			
2 Repetition of previous phase activities if necessary																																								
PHASE III PROBLEM INTERPRETATION																						BC	CD	CD	BC	BC	BC	CD	BC	BC	CD	BC	CD	BC	CD	DC	BC	AB	AB	BC
1 Compile findings & if necessary extrapolate tests (thermological etc.)		◆			◆	◆	◆				◆		◆	◆	◆	◆				◆	◆																			
2 Collate data into primary & secondary factors		◆			◆											◆		◆		◆	◆																			
3 Synthesize (tests & data)		◆			◆	◆	◆				◆		◆	◆	◆	◆		◆		◆	◆																			
4 Develops arguements & problem interpretation																																								
a causes	◆			◆	◆		◆	◆			◆		◆	◆	◆	◆		◆		◆	◆																			
b effects	◆			◆	◆		◆	◆			◆		◆	◆	◆	◆		◆		◆	◆																			
c reasoning																																								
PHASE IV PROBLEM REQUIREMENTS, OPPORTUNITIES & SOLUTIONS																						CD	CD	CD	CD	CD	CD	CD	CD	CD	CD	CD	CD	CD	CD	CD	CD	BC	BC	BC
1 Extrapolate problem requirements																																								
2 Provide alternate solutions & opportunities																																								
3 Selection & implementation																																								
PHASE V POST-OCCUPANCY EVALUATION																						BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	BC	AB	AB	AB	BC
Same as phases I & II																																								
BUILDING ENCLOSURE THERMAL DEFICIENCY CAUSES																																								
1 Insulation ommission & discontinuation																																								
2 Insulation displacement																																								
3 Insulation deficiency (saturation, squashed, short)																																								
4 Air seal failure or discontinuation																																								
5 Vapour barrier failure or discontinuation																																								
6																																								
7																																								
8																																								
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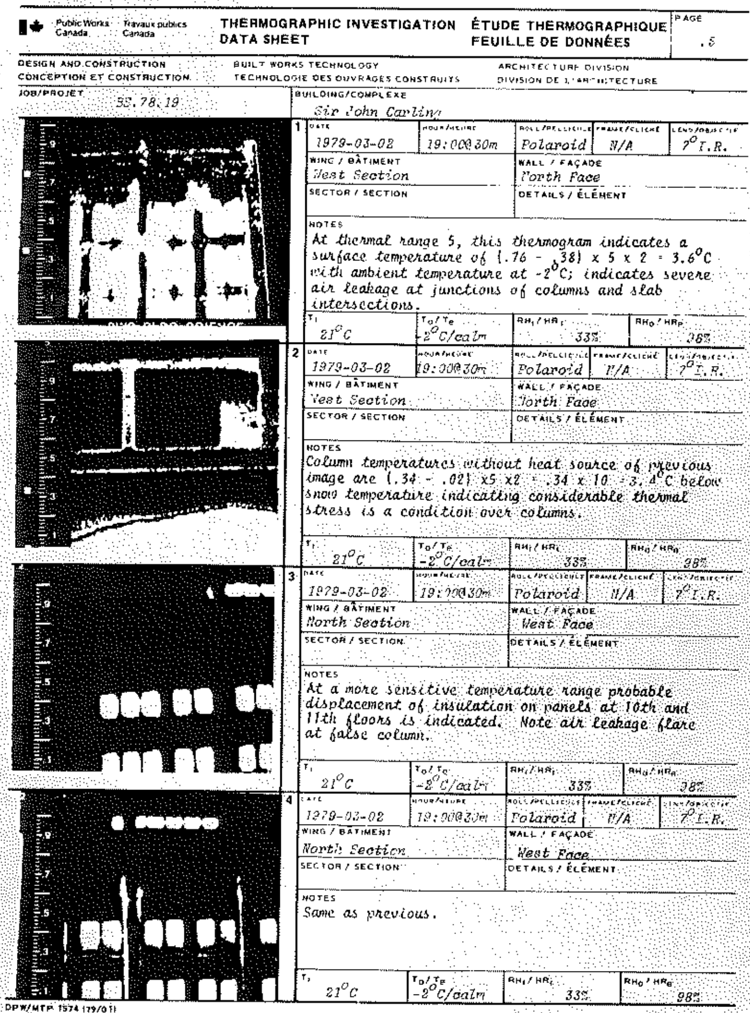
Fig. 3 (Continued)



Public Works Canada / Travaux publics Canada

THERMOGRAPHIC INVESTIGATION DATA SHEET — **ÉTUDE THERMOGRAPHIQUE FEUILLE DE DONNÉES** — PAGE .5

DESIGN AND CONSTRUCTION / CONCEPTION ET CONSTRUCTION — BUILT WORKS TECHNOLOGY / TECHNOLOGIE DES OUVRAGES CONSTRUITS — ARCHITECTURE DIVISION / DIVISION DE L'ARCHITECTURE

JOB/PROJET: 35.78.19 — BUILDING/COMPLEXE: Sir John Carling

No.	DATE	HOUR/HEURE	ROLL/PELLICULE	FRAME/CLICHÉ	LENS/OBJECTIF
1	1979-03-02	19:00@30m	Polaroid	N/A	7^{O} I.R.
2	1979-03-02	19:00@30m	Polaroid	N/A	7^{O} I.R.
3	1979-03-02	19:00@30m	Polaroid	N/A	7^{O} I.R.
4	1979-03-02	19:00@30m	Polaroid	N/A	7^{O} I.R.

No.	WING / BÂTIMENT	WALL / FAÇADE	SECTOR / SECTION	DETAILS / ÉLÉMENT
1	West Section	North Face		
2	West Section	North Face		
3	North Section	West Face		
4	North Section	West Face		

NOTES:

1. At thermal range 5, this thermogram indicates a surface temperature of (.76 - .38) x 5 x 2 = 3.6°C with ambient temperature at -2°C; indicates severe air leakage at junctions of columns and slab intersections.
2. Column temperatures without heat source of previous image are (.34 - .02) x5 x2 = .34 x 10 = 3.4°C below snow temperature indicating considerable thermal stress is a condition over columns.
3. At a more sensitive temperature range probable displacement of insulation on panels at 10th and 11th floors is indicated. Note air leakage flare at false column.
4. Same as previous.

No.	T_I	T_O/T_E	RH_I/HR_I	RH_O/HR_E
1	21°C	-2°C/calm	33%	98%
2	21°C	-2°C/calm	33%	98%
3	21°C	-2°C/calm	33%	98%
4	21°C	-2°C/calm	33%	98%

DPW/MTP 1574 (79/01)

TITLE

Figure A

Thermogram of south corner showing air leakage patterns at 11th floor and panel junction.

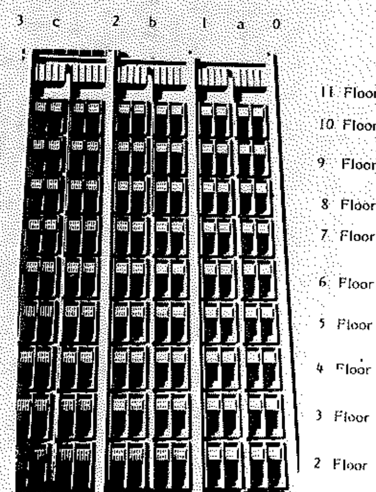
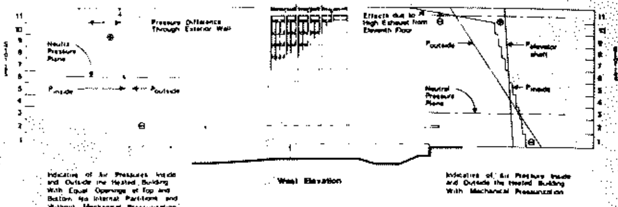


PHOTO 1

South Elevation, East Section, 11th Floor shows typical precast assembly.

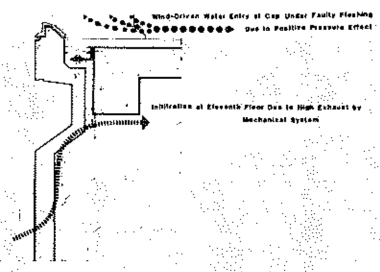
Note: degradation at 9th Floor horizontal joints on columns. This occurs from the fourth floor up.

Fig. 4 Sample format for thermographic data collection (PWC Thermographic Investigation Data Sheet)



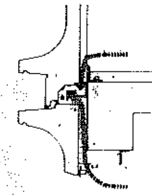
Note: Probable infiltration routes & condensation accumulation at floor & corner intersection.

Figure



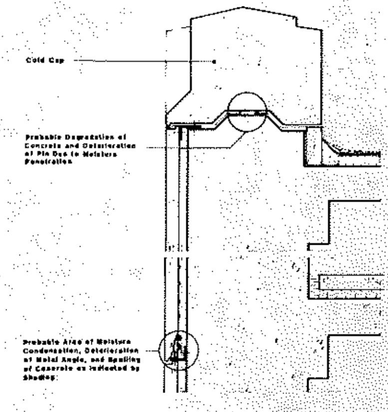
Section At Eleventh Floor - Through Precast Panel
Not to Scale

Figure



Section At Typical Wall - Through Glazing
Not to Scale

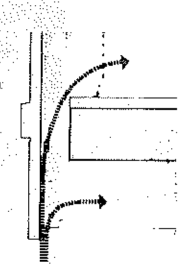
Figure



Section At Eleventh Floor - Through Column
Not to Scale

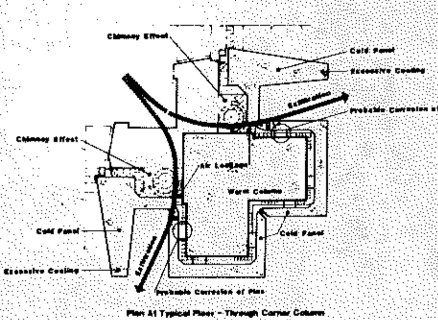
Figure This Figure should be read in conjunction with Photos 7 & 8.

Note: Primary infiltration routes contributing significantly to low temperatures and occupant discomfort.



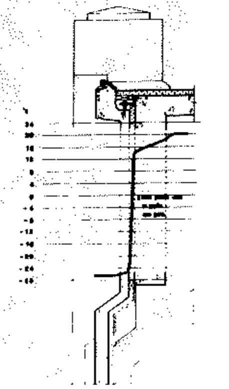
Section At Second Floor - Adjacent To Column
Not to Scale

Figure



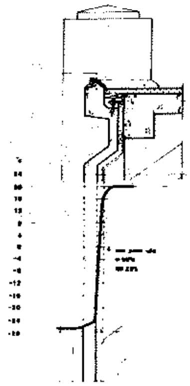
Plan At Typical Floor - Through Corner Column
Not to Scale

Figure The Illustration demonstrates the primary design factors contributing to the indicated mechanisms of air leakage and condensation. This Figure should be read in conjunction with the following thermal gradients to appreciate the extent of cold surfaces (refer to photos 7 and 8).



OUTSIDE ENVIRONMENT
100 mm Precast Concrete
75 mm Insulation
450 mm Concrete Beam
INSIDE ENVIRONMENT

Figure All thermal gradients are based on stable state conditions.



OUTSIDE ENVIRONMENT
150 mm Precast Concrete Panel
50 mm Polystyrene Insulation
20 mm Cement Rendering
INSIDE ENVIRONMENT

Figure Condensation will occur on the inside face of precast panel wherever failure of air seal exists. It is at the lower section of this panel that severe air leakage exists at all junctions of column and floor (refer to thermograms).

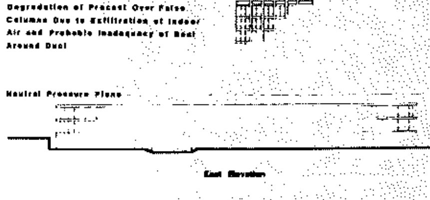
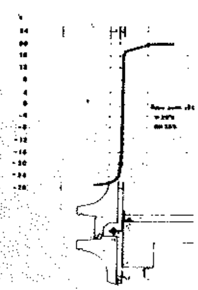


Figure Evidence of degradation of precast at sealed joints can be seen in photo 9.



OUTSIDE ENVIRONMENT
100 mm Precast Concrete Panel
50 mm Insulation
INSIDE ENVIRONMENT

Figure

Fig. 4a Examples of Building Science data sheets presenting conclusions drawn from phases one and two of the methodology

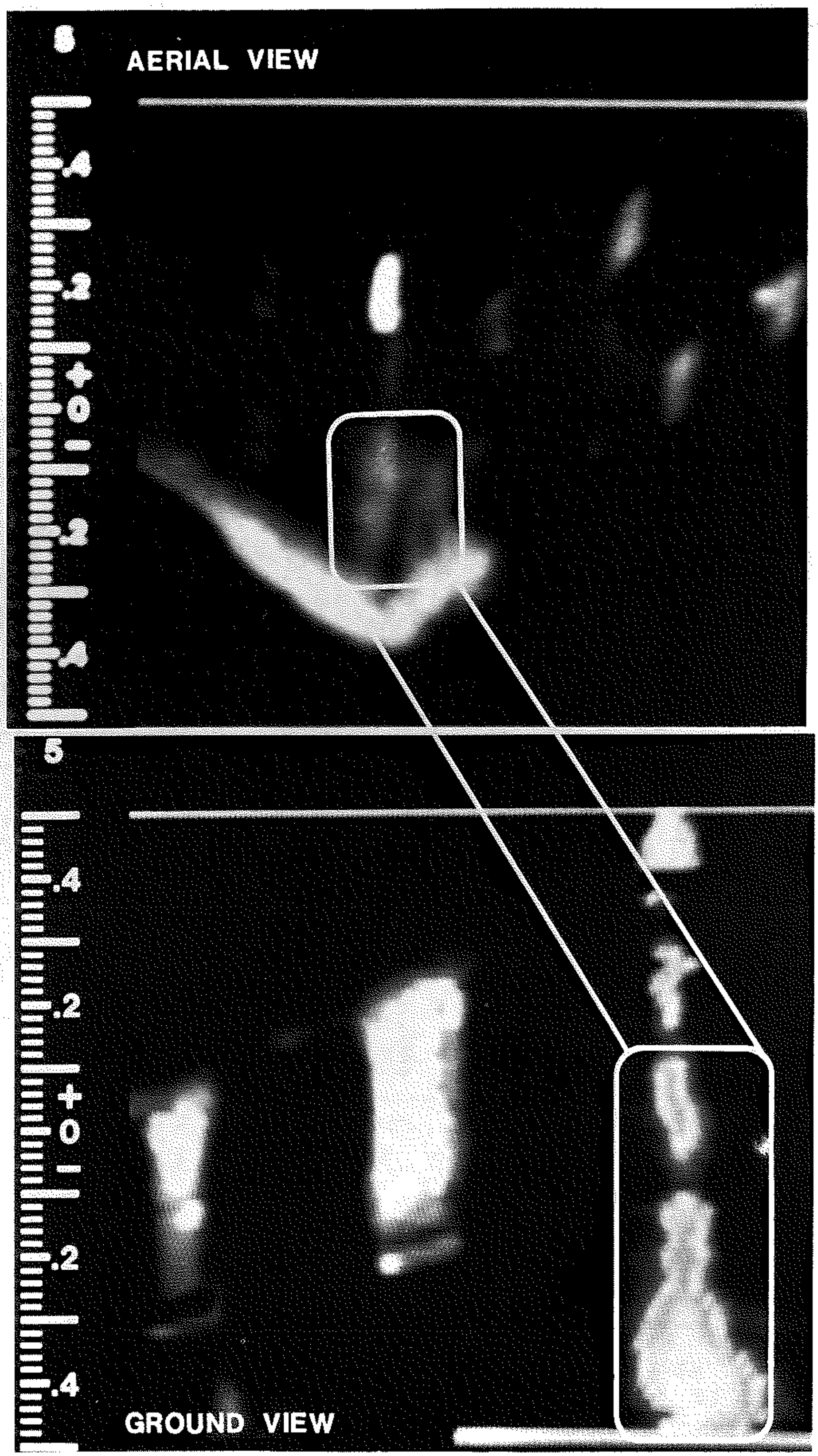


Fig. 5

Examples of an aerial thermogram detecting a thermal anomaly and a thermogram from a subsequent ground survey recording detailed data of the area identified