USING THERMAL CAMERAS TO PROMOTE ENERGY EFFICIENCY IN BUILDINGS

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As part of the UBC Sustainability Scholars program
July 20th, 2016

EXECUTIVE SUMMARY

The City of Surrey has recognized building energy efficiency as an important focus in its efforts to improve affordability and protect the environment. Energy efficient buildings are more durable, lead to long term savings for homeowners, provide health benefits for occupants, and reduce the emissions of greenhouse gases.

Thermographic technology can help support building energy efficiency initiatives. In the past few decades, thermal cameras (also referred to as “thermal imagers”) have emerged as a popular tool for surveying building energy efficiency. Modern handheld thermal cameras are capable of measuring temperatures, assessing heat loss, identifying missing or degraded insulation, and locating sources of moisture. Thermal cameras offer a non-destructive means of diagnosing building conditions, and can rapidly visualize information that would otherwise be difficult to collect and communicate.

Although fast-paced technological development has led to a dramatic reduction in prices, thermal cameras remain a costly investment, with handheld devices ranging from several hundred to several thousands of dollars. Furthermore, thermal images are frequently misinterpreted, and operators require a foundational understanding of both building science and the physics of heat transfer.

The following report was produced in cooperation between the City of Surrey and the UBC Sustainability Scholars program. It provides an overview of thermographic technology and its applications in evaluating building energy efficiency.

- Part 1 introduces the physical principles that enable heat to be detected by thermal sensors.
- Part 2 explores how thermal cameras can assess the heat dynamics that determine a building’s energy use.
- Part 3 summarizes operational considerations for acquiring and interpreting thermal images.
- Part 4 summarizes key technical specifications, which may inform the selection of an appropriate thermal camera model.
- Part 5 describes existing municipal and community programs that use thermal imaging, as well as the results of interviews with representatives from these programs.
- Part 6 describes four potential thermal imaging programs that could be implemented in the City of Surrey.

By reviewing this report, it is expected that readers will be informed of both the benefits and the challenges of using thermal cameras to survey energy efficiency, and will be better equipped for evaluating the feasibility of incorporating this technology in municipal programs.

Cover image: Drone Thermal Camera. http://www.drone-thermal-camera.com/

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1. INTRODUCTION TO THERMAL IMAGING

1.1. Fundamental principles

1.1.1. Physics of heat

Particles of matter are in a state of constant motion, which creates internal energy known as "thermal energy". The average thermal energy within an object is measured by its temperature. The higher the temperature, the faster the particles within that substance are vibrating. Thermal energy can also be transferred from one system to another in a process simply known as "heat".

The branch of physics known as "thermodynamics" is concerned with the principles that govern the transfer of heat. In accordance with the laws of thermodynamics, thermal energy will flow from a hot system to a colder one, provided a suitable physical pathway is available. The greater the difference in temperature between the two systems, the higher the rate of this flow will be. This process continues until an equilibrium has been established.

The transfer of thermal energy can be accomplished through three different modes: convection, conduction or radiation. Generally speaking, heat is transferred between solids through conduction (e.g. a hand on a warm cup of coffee) and between liquids and gases through convection (e.g. the cooling effects of a breeze of air). While both of these modes have practical implications on thermal imaging, it is thermal radiation that is directly detected by thermographic devices.

KEY DEFINITIONS

Though they may be used interchangeably, the following terms are separate scientific concepts.

Thermal energy
The *total* kinetic energy possessed by an object or a system. Measured in Joules (J) or calories (cal).

Temperature
The *average* kinetic energy possessed by an object or a system. Measured in degrees Fahrenheit (F) or Celsius (C). The Kelvin scale uses the degree Celsius as its incremental unit.

Heat
Energy transferred across the boundary of one region to another, either in the form of radiation, convection or conduction. Measured in Joules per second (J/s), calories per second (cal/s) or Watts (W).

1.1.2. Heat and the electromagnetic field

Heat is transferred through radiation in the form of electromagnetic waves. Many of these waves are familiar to us, and are generally characterized by their wavelength. For example, x-rays have extremely short wavelengths, in the order of a fraction of a millimeter, while radio waves can measure several kilometers. Visible light is a form of electromagnetic radiation, with specific wavelengths associated with different colours. The motion of particles of any object will generate some degree of this energy, which is known as thermal radiation. This energy then travels outwards, and can then be re-absorbed by other objects. Despite the millions of kilometers between them, every day the Earth is heated by the thermal radiation from the sun. At a local scale, this same mechanism applies to campfire, which heats its surroundings without being directly in contact with them.

Figure 1. The hottest part of this iron rod glows with white light. Further from the tip, the light shifts from yellow, to red, and then to infrared (which is not visible). Image: Shutterstock[1].

Once emitted, thermal radiation behaves in many of the same ways as visible light, namely it can be reflected (e.g. a reflection in a mirror) or transmitted (e.g. seeing through a clear pane of glass). Our visual perception of thermal radiation is, in many ways, dependent on the amount of energy being radiated. Heat from the sun is clearly visible in the form of sunlight, while a heated iron will glow. Yet, lesser sources of heat do not show any visible signs of their temperature. Very hot objects radiate thermal energy at wavelengths that are within the visible spectrum, while cooler objects emit radiation at longer wavelengths which cannot be seen. However, while this longer wave radiation is not naturally visible to humans, it is still being emitted and can therefore be detected using specially designed sensors.

1.2. Physics of thermographic imaging

1.2.1. Thermal cameras

Some species of snake are able to locate warm-blooded prey by detecting the heat of their bodies. This is due to special organs which are sensitive to radiation that is imperceptible to human eyes. This radiation is generally within a section of the electromagnetic spectrum known as the “infrared”; radiation with wavelengths between 700 nanometers (0.0007 mm) and 1 mm. Infrared radiation is particularly relevant to thermal imaging, since objects near room temperature emit most of their thermal radiation within this range.

The function of a thermographic camera is to detect infrared radiation remotely, convert it to an electronic signal, and then produce an image representing the radiation’s intensity. In this sense, it is analogous to a common camera, which instead detects visible light. Thermographic technology has benefited from recent technological advances in optics, digital memory, image processing algorithms and specialized coatings for thermal sensors, and consumer-grade cameras are now readily available.

1.2.2. Factors influencing an object’s thermal image

Thermal cameras do not detect heat directly, only the infrared radiation that is generates. To interpret the images produced by these devices, known as “thermograms”, it is important to understand the factors that influence how this radiation is dispersed into the environment.

[1] http://www.shutterstock.com

RADIOSITY

The total radiation leaving an object's surface, known as its "radiosity", is the sum of the following three components:

Incident radiation (*radiosity*) = Emitted radiation (*emissivity*) + Transmitted radiation (*transmissivity*) + Reflected radiation (*reflectivity*)

1.2.2.1. Radiosity

When directed at an object, a camera's detector will receive a certain quantity of infrared energy. A portion of this energy is emitted directly by the object, through thermal radiation. This radiation relates to the object's internal thermal energy, and is generally the focus of interest for the camera's operator. Some of the energy detected by the camera, however, is reflected off the object's exterior after originating from elsewhere in its environment (e.g. the sun's warmth reflected off a metallic surface). Radiated energy may also be transmitted through the object without being absorbed (e.g. heat travelling through a thin sheet of plastic). These three components—emissivity, reflectivity and transmissivity—form the total amount of radiation emanating from an object, and are known collectively as the entity's "radiosity". However, only an object's emissivity is an indicator of its true internal temperature. This property is explored in more detail below.

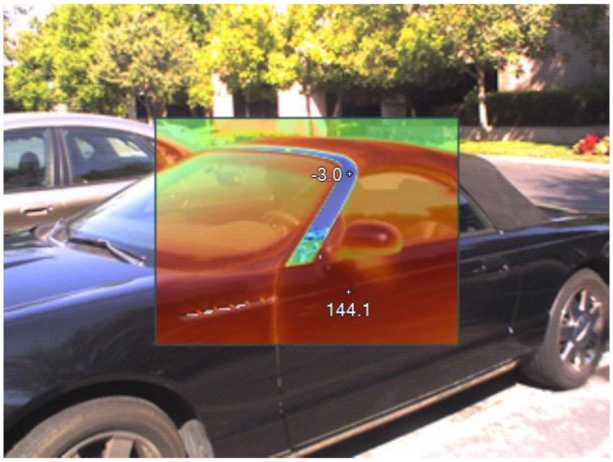

Figure 2. Infrared radiation reflected off a chrome strip. Image: MoistureView.[2]

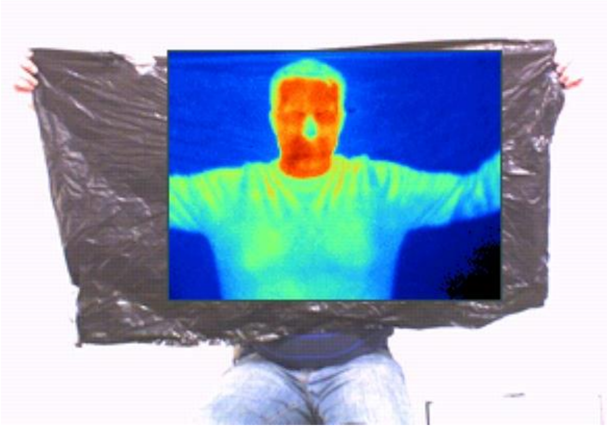

Figure 3. Infrared radiation transmitted through an opaque sheet of plastic. Image: MoistureView[3].

1.2.2.2. Emissivity

A material's emissivity is defined as its efficiency in emitting thermal radiation. In physics, a "black body" is a theoretical substance that absorbs and emits radiation at a maximal rate. In reality, no such material exists, and so an object's

[2] http://www.moistureview.com/blog-015
[3] http://www.moistureview.com/blog-06

EMISSIVITY

The following table presents the emissivity coefficients for some common materials.

MATERIAL	EMISSIVITY	MATERIAL	EMISSIVITY
Aluminum foil	0.03	Limestone	0.92
Aluminum roofing	0.24	Mortar	0.90
Asphalt	0.88	Nickel, electroplated	0.03
Brass, oxidized	0.60	Nickel, solar absorber	0.05 - 0.11
Brass, polished	0.04	Paints, silver chromatone	0.24
Brick	0.90	Paints, acrylic	0.90
Concrete, rough	0.91	Paints, gloss	0.85
Copper, electroplated	0.03	Paints, epoxy	0.85
Copper, oxidized	0.76	Paper, roofing	0.88 - 0.86
Glass, polished	0.87 - 0.92	Plaster, rough	0.89
Glass, smooth	0.91	Silver, polished	0.02
Granite	0.44	Snow	0.82
Gravel	0.30	Soil	0.94
Ice	0.96 - 0.97	Water	0.90

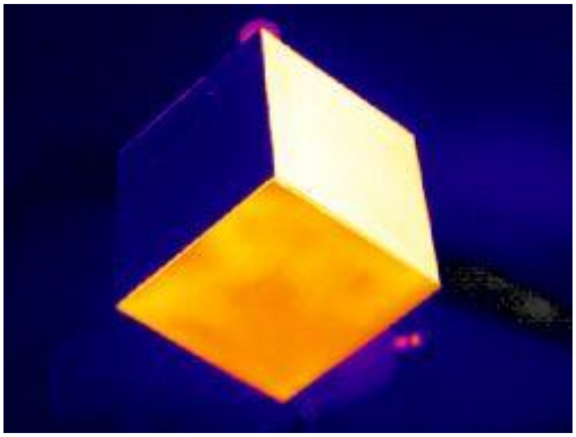

Figure 4. A Leslie cube. To demonstrate the effects of surface emissivity, each side of this cube was coated with a different material. Although each side appears different when viewed through a thermal camera, the internal temperature is the same. Image: Brandenburg Technical University.[4]

emissivity is measured as the ratio of its radiative capacity to that of a hypothetical black body. In practical terms, if an object's emissivity is close to 1.00, then it emits thermal radiation effectively, while a value significantly lower than 1.00 indicates that it will retain heat. Another way to think of this is that a high emissivity object rids itself of heat easily while a low emissivity object stores it. Awareness of this property is critical to interpreting thermal images. Two objects with similar temperatures but different emissivity coefficients will radiate energy at distinct intensities, and will therefore *appear differently when targeted by a thermal camera*.

Everyday materials have a wide range of emissivity values. Most metals have low emissivity (e.g. silver: 0.02, aluminum: 0.03) while substances like brick, glass or water have

[4] http://www.th-brandenburg.de/~piweb/projekte/thermo_galerie_eng.html

emissivity values over 0.90. The surface texture of an object can have a significant impact on its emissivity as well. Though they may be composed of identical materials, a polished surface will have a much lower emissivity than a roughened one. In fact, creating grooves and cavities in a surface is a commonly used technique to deliberately increase emissivity. Oxidization and corrosion have considerable effects as well: while polished brass has an emissivity close to 0.04, oxidization can be increase that value to 0.60.

1.2.2.3. Angle of incidence

In the same way that the reflection of visible light can be oriented by shifting the angle of a mirror, so too can infrared waves be focused into a single outgoing direction. This, once again, is highly dependent on the material being observed. For example, both glass and sand have similar emissivity values (approximately 0.92). However, infrared radiation emitted by glass will be concentrated into a single direction, while radiation from sand will be evenly dispersed. In this respect, we qualify materials as either "specular", for which the intensity of emitted radiation is dependent on direction, or "diffuse", for which it is not. This is an important practical consideration, since specular emitters will vary in appearance depending on the angle at which they are observed, also known as their "angle of incidence".

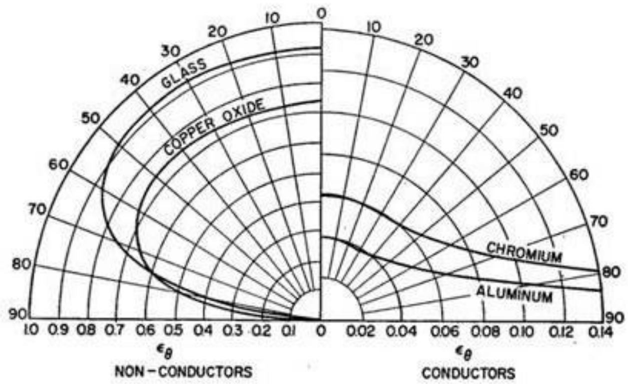

Figure 5. The effect of the angle of incidence on the perceived emissivity of various materials. Note how, when viewed between 80 and 90°, the emissivity of glass is lower than 0.50, while it rises to above 0.90 at a perpendicular angle. Image: MoistureView.[5]

1.2.2.4. Temperature differential

The wall of a warm house will emit heat on a cold winter day, yet that same wall will be heated by its surroundings in the summer, particularly if the inside of the house is being air conditioned. According to the laws of thermodynamics, this is because heat always flows from hot to cold. The difference in temperature between two objects (commonly abbreviated to ΔT) establishes not only the direction of this flow, but also its intensity. Although heat will continue to be transferred until both entities have achieved thermal equilibrium, the rate of transfer will decrease as ΔT narrows. Temperature differential is therefore a fundamental variable in the dynamics of heat radiation, since the energy radiated by an object depends not only on its own characteristics (internal temperature, emissivity, etc.), but also the temperature of its surroundings. Consequently, ΔT should be taken into account when targeting an object with a thermal camera, as ambient air temperature and wind conditions can influence the amount of radiation that it emits.

[5] http://www.moistureview.com/blog-014

2. APPLICATIONS OF THERMAL IMAGING IN BUILDING INSPECTION

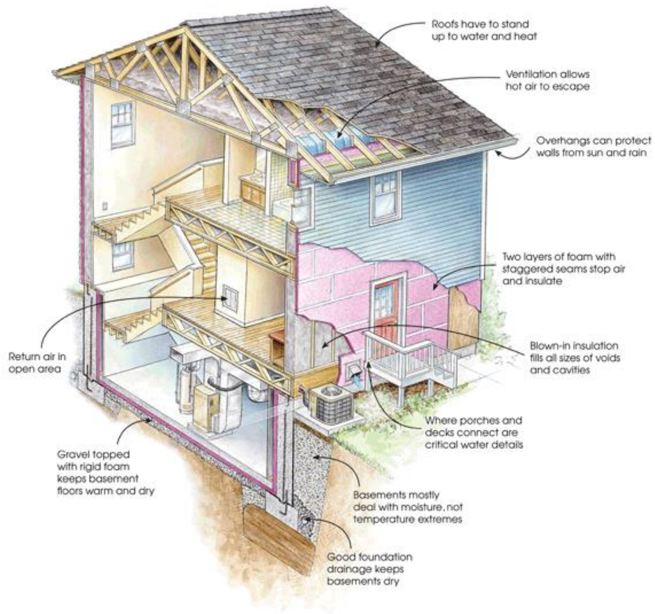

Figure 6. Cross section showing a building's outer shell and layers of thermal insulation. Image: Green Building Advisor.[6]

2.1. Energy efficiency

2.1.1. Building envelopes

A building's envelope is the constructed layer that separates the indoor, typically conditioned, environment from the outdoors. A building envelope normally comprises walls, windows, roofs, floors and doors. Specialized components such as impermeable membranes, insulating materials and weatherstripping have been developed to prevent unwanted heat loss, air flow or moisture build-up through the envelope. A properly constructed and designed envelope is necessary to secure the health, safety and comfort of the building's occupants, as well as ensure the building's long-term durability.

The envelope's quality is also directly linked to the energy efficiency of the building. Structures with poor air barriers (a.k.a.: "leaky") or inadequate insulation transfer energy at a greater rate between indoor and outdoor environments. This puts additional demand on mechanical heating systems, which in turn increases energy consumption. Given that, in cold climates, approximately 50% of a building's energy is used by heating, ventilation and air conditioning (HVAC) systems, the potential for energy reduction through a well-designed building envelope is substantial. Increased energy efficiency translates into savings for building owners, reduced strain on energy infrastructure and potential environmental benefits.

2.1.2. Heat dynamics within buildings

There are three main factors to consider when assessing the heat exchanges that occur within a building: the flow of conductive heat, the flow of air and the intrusion of water. The prevention and management of these three phenomena is a main focus of energy efficient building design.

2.1.2.1. Conductive heat transfers

Conduction is one of the three fundamental modes by which heat is transferred. Conduction occurs through the solid components of a building; for instance, when heat passes from the warm inner side of a wall to its cooler exterior. This transfer occurs more easily through certain substances than others, a

[6] http://www.greenbuildingadvisor.com/

property known as “thermal conductivity” or its inverse “thermal resistivity”. Insulating materials have low thermal conductivity—they are deliberately engineered to impede the transfer of conductive heat. This insulating capability is quantified by a material’s R-value and its reciprocal, the U-factor, which measure the change in convective heat in a given area over time. More conductive objects with low R-values (e.g.: pipes, metal window frames or studs) can create pathways through which large amounts of heat are transferred. The strategic placement of insulation aims to interrupt these transfers. Missing, poorly designed, improperly assembled or damaged insulating layers are common issues in building construction, and are responsible for significant losses of heat.

2.1.2.2. Convective air flow

Air movement through a building’s envelope and within the building itself is another major source of energy loss. It is commonly known that warm air rises to the upper levels of a home, leaving the ground floor and basement relatively cooler. This is due to convection, the mode by which heat is transferred through fluids. Some types of convective air flow are desirable and actively induced by home owners. These range from operating ceiling or exhaust fans to opening a window on a hot day. In many circumstances, however, air flow is unintentional, and can be the cause of substantial unwanted heat loss. Air leakages are common in the various holes and passages created for electrical wiring, plumbing, ducts, vents, chimneys and recessed lights. Basement rim joists, where a building’s foundation connects with the wood framing, are also common areas of concern. Leaks in and around the attic are particularly problematic: as valuable heated air rises, it can escape from living spaces and create a vacuum that will draw in cooler air from other openings. Furthermore, the performance of insulating materials can be compromised as air passes through cavities in the floors and walls. When carefully sealed, the various types of weather-resistant membranes used in a building’s enveloped act as effective air barriers, while caulking, tape and weatherstripping are applied to prevent leakages around components such as doors and windows.

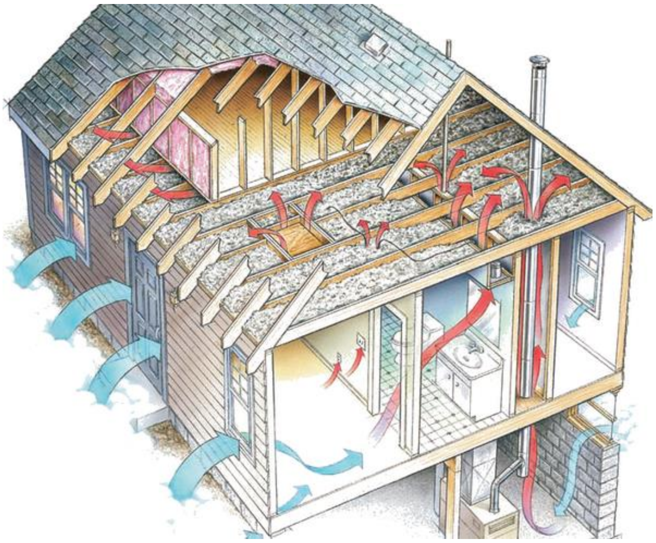

Figure 7. Warm air rises through a building, while cool convective air currents infiltrate through the gaps in the structure’s air barrier. Image: All In One Insulation.[7]

2.1.2.3. Water intrusion

Preventing the permeation of moisture is one of the main functions of a building’s envelope. Unwanted moisture can penetrate into a building through rainwater leakages, vapor diffusion, leaking water pipes,

[7] http://allinoneinsulation.com/insulation/the-all-in-one-system/

groundwater intrusion, left-over moisture from construction materials, or through moist air currents. Though moist air can be an issue in and of itself, many of its most adverse effects occur when air is cooled past the “dew point”: the temperature at which water vapor condenses into liquid form. Prolonged exposure to water can damage building materials, while damp conditions foster the growth of mold and bacteria, which can severely degrade indoor air quality and endanger the health of the building’s occupants. With regards to heat dynamics, moisture can have either a cooling or a warming effect on buildings. Water can reduce surface temperatures through evaporative cooling, a process by which heat is transferred into the air as water turns to vapor. Conversely, water’s capacity to store heat can warm certain parts of the building. The thermal conductivity of insulating materials (section 2.1.2.1) will also increase when permeated by water, thus undermining their effectiveness. Many of the components of a building’s air barrier, such as properly sealed building assemblies and air retarding membranes prevent the infiltration of moist air. Other key features for preventing water intrusion include water repellant finishes, drainage systems, vapor retarders, properly function HVAC systems and correctly installed plumbing.

2.2. Thermal imaging for building inspections

2.2.1. Techniques for surveying heat loss

To optimize a building’s use of energy, unwanted heat transfers must be identified and corrected. Although air drafts in older buildings can sometimes be felt on a cold day, many areas of heat loss are difficult to perceive without the use of specialized tools and techniques. For instance, an estimate of a building’s heat loss can be calculated using the surface area and the R- or U-values of its building materials. Borescopes allow hard-to-access cavities to be inspected visually. Blower door tests and smoke guns can be used to detect air leakages while moisture meters can measure moisture levels in wood, concrete or plaster.

With the development of modern thermographic technology, handheld thermal cameras have emerged as a potential tool for building inspections. Noted for being non-destructive, thermal cameras are now commonly used to identify construction problems, design flaws, aging building materials and other sources of preventable heat loss. In many cases, locating issues on a thermal image is less time-consuming than with traditional survey methods, while providing the added benefit of visual documentation that can be included in inspection reports.

2.2.2. Imaging the flow of heat

Although heat is transferred through conduction, convection and radiation, thermal cameras are only capable of directly measuring radiated heat. However, this does not mean that conductive heat loss or convective air currents cannot be located. Conduction and convection affect the temperature of a building’s elements, which in turn influences the level of heat that they radiate. As such, unusual levels of thermal radiation may be signs of problematic areas. For instance, an abnormally warm section of a wall might be lacking insulation, while a particularly cool window frame might be leaking air.

2.2.3. Detecting moisture

The prevention of moisture build-up is a significant concern in building maintenance. Although thermal cameras cannot directly measure water content, its presence can often be inferred from thermal images. Evaporating water will cool damp surfaces (section 3.5.1) allowing thermal cameras to locate moisture that would be otherwise invisible to the naked eye. Condensation occurs in particularly cool and humid sections of a structure. By locating areas with temperatures below the dew point, inspectors can locate areas that are at-risk for moisture build-up.

Figure 8. The true temperature of a target can only be estimated using a thermal camera if its emissivity coefficient is known. Image: FLIR.[8]

2.2.4. Quantitative versus qualitative analysis

Thermal images are generally analyzed through either quantitative or qualitative approaches. Quantitative analysis requires the true temperature of a target to be determined. Some basic requirements must be met for this to be possible. First, the target's emissivity must be known. As discussed in section 1.2.2.2, emissivity is the efficiency of an object in emitting thermal radiation. Many thermal cameras have an emissivity setting. By adjusting this setting to the emissivity value of the target, the device will compute its temperature.

However, the effects of reflectivity and transmissivity (section 1.1.2) must also be accounted for. This can be a significant hurdle, as these factors can be difficult to quantify and can invalidate readings even when the correct emissivity is set. Quantitative analysis is a difficult undertaking, and is more common for industrial applications that require precise temperature measurements for manufacturing processes.

Qualitative analysis, in contrast, does not require any absolute temperature measurements. Instead, the distributions and relative variations in temperature are the focus of interest. This type of analysis is most common in building inspections, where the primary objective is to locate air leakages, missing insulation or other construction flaws that cause deviations from an expected baseline temperature.

TYPES OF BUILDING ANALYSIS

Quantitative
- Less common for building inspection.
- Measure absolute temperature.
- Example: Locate areas with temperatures below dew point.

Qualitative
- Most common for building inspection.
- Analyze distribution and variations in temperature.
- Example: Locate missing insulation or air leakages.

[8] http://www.flir.ca/home/

3. OPERATIONAL CONSIDERATIONS

3.1. Proper acquisition and interpretation of thermal images

Although thermal cameras are potentially useful tools for assessing the energy efficiency of buildings, misuse of these devices is common, and thermal images can easily be misinterpreted. Heat fluctuations are inherent to buildings, and are both expected and generally within the allowed limits of construction standards. Not all apparent anomalies are due to faulty building components, and so careful interpretation of thermal images is needed. For thermal cameras to be used effectively, operators must be firmly grounded in the fundamental laws of heat transfer, the operation of the devices, and the various factors that can affect their readings.

While parts 1 and 2 detailed the foundational physical principles of heat transfer and how they apply to the thermal dynamics of a building, the following section will highlight some common practical considerations and challenges associated with building inspections. Note that this section of the report should not be considered a substitute for formal training in the operation of thermal imaging equipment, nor an exhaustive list of factors that may complicate the interpretation of readings.

FACTORS INFLUENCING THERMAL IMAGES

The following is a non-exhaustive list of variables that may influence the images recorded with a thermal camera.

- Emissivity of object
- Distance of camera to object
- Size of object
- Relative humidity
- Ambient temperature
- Atmospheric temperature
- External optics temperature
- External optics transmission
- Temperature span (ΔT)
- Temperature range
- Wavelength range of camera
- Angle of observation
- Optical properties of matter between camera and object
- Use of image filters
- Thermal reflections
- Wind speed
- Shadow effects of nearby objects
- Moisture
- Thermal properties of objects

3.2. Operation of the device

3.2.1. Display

The levels of infrared radiation incident on thermal camera's sensor are displayed as an image on its screen. Depending on the model of the device, this image can be represented through various levels of gray, or in a pseudo-colour scheme. In Figure 9, red and orange colours represent high levels of infrared radiation, which are associated with high temperatures, whereas low radiation levels are shown in blue.

An important parameter for visualizing a thermal camera's readings is the "span" of the image's colour scheme: the difference in colour between the highest and lowest temperature values in the image. Figure 9 displays an identical scene using two different spans. The left-hand image uses a wide span between 18 to 35°C, which captures the full temperature range across the room. In contrast, a narrow span has been applied to the right-hand image. Although the temperature of the lighting fixture in the bottom-left corner of the image is now outside of the span, subtle temperature variations above the window are now much easier to recognize. While many device models will perform automatic span adjustments depending on the instrument's target, it is often possible to control the span manually. It is advisable to keep the span as narrow as possible in order to accentuate the visible detail in a thermal image.

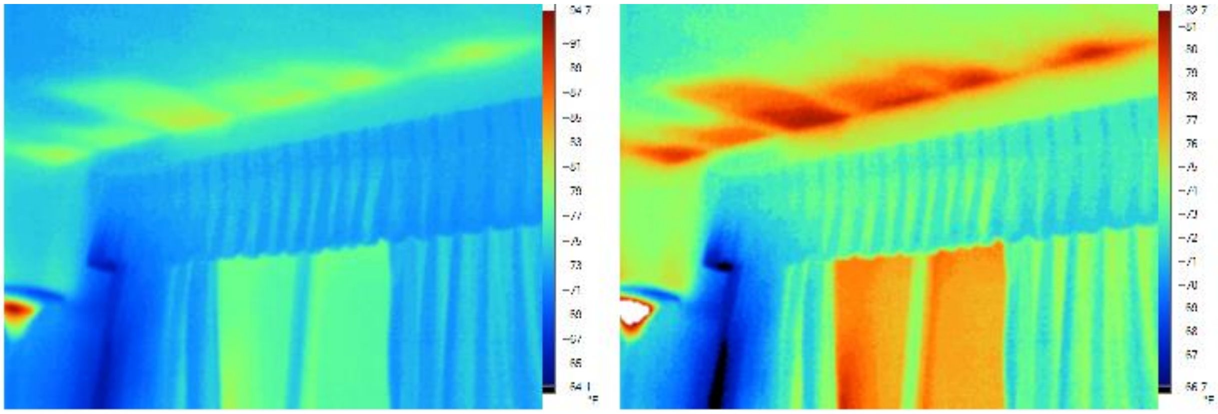

Figure 9. Two thermal images of a room with a light fixture and a large window. Although the scene is identical and the colour gradient is the same, the instrument's readings are displayed using different temperature spans. Image: Thermal Imaging Blog.[9]

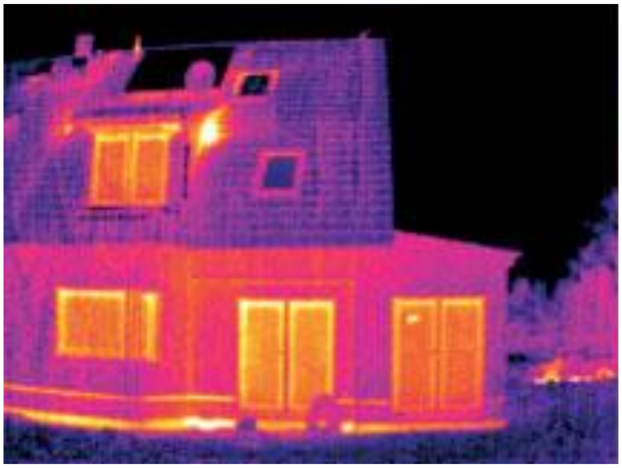

Figure 10. Different materials are used for this house's roof, outer walls, windows and frames. Since each material possesses a distinct emissivity coefficient, the relative temperatures of these materials cannot be compared using a single thermal image. Image: Vollmer & Möllmann, 2010.[10]

3.2.2. Viewing angle

As discussed in section 1.2.2.3, the thermal radiation of a material is either specular or diffuse. While diffuse radiation is emitted evenly in all directions, the level of radiation detected from a material with a specular quality will be highly dependent on the angle at which it is viewed. In the case of highly specular substances such as glass or oxidized copper, the variations in perceived temperature can be considerable. It is therefore ideal to view targets at a perpendicular or 90° angle from its surface, though in practice, this may not always be possible.

3.2.3. Accounting for emissivity

When quantitative analysis is required—for instance, when attempting to locate areas below dew point—a target's emissivity must be known for accurate temperature readings to be

[9] http://thermal-imaging-blog.com/index.php/2010/02/10/level-and-span-a-definition/#.V5AHJbiANHx

[10] See References section

acquired. Several of the challenges associated with this type of analysis are explained in section 2.2.4. Scientifically determined emissivity values are available from both online and published resources (see Brewster, 1992), and many device models will include easily accessed tables for common materials. It should be noted that temperature readings will be most accurate for objects with high emissivity. When determining the temperature within a given area, it is therefore recommended to select high-emissivity targets whenever possible.

Even when performing a qualitative analysis, emissivity should always be taken into account. As stated in section 1.2.2.2, two objects with similar temperatures will appear differently on a thermal image unless their emissivity values are identical. It is therefore important that relative temperature comparisons only be made between objects of the same material (Figure 10).

3.3. Documentation

Thermal images are an excellent form of documentation and can contribute to detailed and informative inspection reports. Given the wide range of factors that can affect thermal readings, however, several variables should be recorded when taking images. Visible photos of the area (which can often be captured using built-in visible cameras) can assist with post-inspection analysis, while a legend of the image's temperature span (see section 3.2.1) is needed to interpret any absolute temperature values that were acquired.

3.4. Optimal conditions for thermography

To reduce the many confounding factors that can affect the accuracy of thermographic readings, several conditions should be met prior to inspection. First, the temperature differential (ΔT) between the building's interior and the outdoors should be as large as possible. As discussed in section 1.2.2.4, a large ΔT will increase the rate of heat exchange between two bodies. In the context of a building, this difference in temperature will intensify heat loss, thus making problematic areas easier to detect. In the city of Surrey, a large ΔT is most likely during the morning of a cold winter day.

Closing all doors and windows will help distinguish the regular convective air currents that flow within the building from unwanted air leakages. Pieces of furniture may obscure problems, and should be moved away from the walls when possible. To achieve optimal accuracy, the housing of a thermal camera should be the same temperature as the ambient air, and so an adaptation time should be allowed before taking any readings (approximately 30 minutes).

VARIABLES TO BE DOCUMENTED

The following is a non-exhaustive list of variables that should be recorded during the acquisition of thermal images. Additional variables should be included depending on the nature of the desired analysis or the procedural norms of the inspection.

- Inside and outside air temperatures
- Inside and outside reflected temperatures
- Inside and outside humidity
- Outside wind speed
- Distance from camera to walls
- Viewing angle
- Emissivity of wall materials

In the case of outdoor thermography, several other environmental factors should be considered (section 3.5.4). Ideal inspection times occur before sunrise, at which point transient heat from the sun will not impact readings. Furthermore, thermography should not be attempted during rainfall, snowfall or foggy conditions, and strong winds should be avoided.

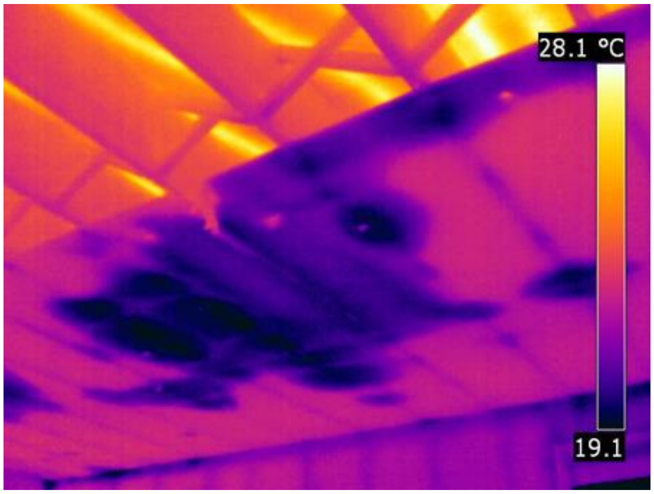

Figure 11. Moisture build-up in a ceiling. Image: Integrity Environmental Services.[11]

3.5. Potential complications

3.5.1. Evaporative cooling

Evaporation is known as a “phase change”: a process by which a substance transforms from a liquid phase to a gas. This transformation requires energy. A liquid will draw in heat from its environment as it evaporates, which will reduce the temperature of the substance itself as well as any surfaces with which it is in contact. Although many mechanical cooling systems employ this principle, it can be observed by simply wearing a wet t-shirt to cool oneself on a hot day.

When viewed with a thermal camera, wet surfaces will often appear cooler due to the effects of evaporative cooling. These situations require careful interpretation. Weather conditions may dampen the outer walls of a building, whose temporarily cool thermal signature may not necessarily be indicative of a problematic area. Though wet surfaces may appear particularly cool in relation to the surrounding environment, it should be noted that abnormally cool conditions may have been responsible for the water build-up in the first place. While the effects of evaporative cooling may be considered a complicating factor in certain analyses, the detection of water itself may also be one of the goals of an inspection.

3.5.2. Thermal bridges

The flow of thermal energy will always seek pathways offering the least amount of thermal resistance. The concentration of transferred heat in these pathways leads to areas with significantly different temperatures than their surroundings. These areas, known as “thermal bridges”, are categorized as being either geometrical or structural, and may or may not represent areas where heat loss is preventable.

Geometrical thermal bridges occur at the junctions of roofs, floors and walls. Conductive heat flow from a flat section of a warm interior wall will be transferred to an equally sized section of the colder exterior wall. In the case of corners, however, the adjacent outer wall will be much larger than the area of the inner corner, leading to a greater opportunity for heat to escape. Although the design of a building can minimize the number of corners and junctions, in many cases geometrical thermal bridges are inevitable.

[11] http://www.integrityenvironmental.ca/thermal-imaging.html

Structural bridges, on the other hand, are caused by the configuration and placement of building materials. This type of thermal bridge includes gaps between layers of insulation, moisture leaks within air cavities, poorly insulated concrete plates, or anchor bolts used to attach insulation to masonry. Depending on the underlying cause, structural bridges can often be mitigated or eliminated altogether. Although structural and geometrical bridges should be distinguished from eachother, their effects can also be compounded. For instance, missing insulation will exacerbate the heat loss caused by the geometrical thermal bridge of a wall junction. These situations are particularly problematic, since the resultant local temperatures can be lowered beneath the dew point, creating moisture and mold problems.

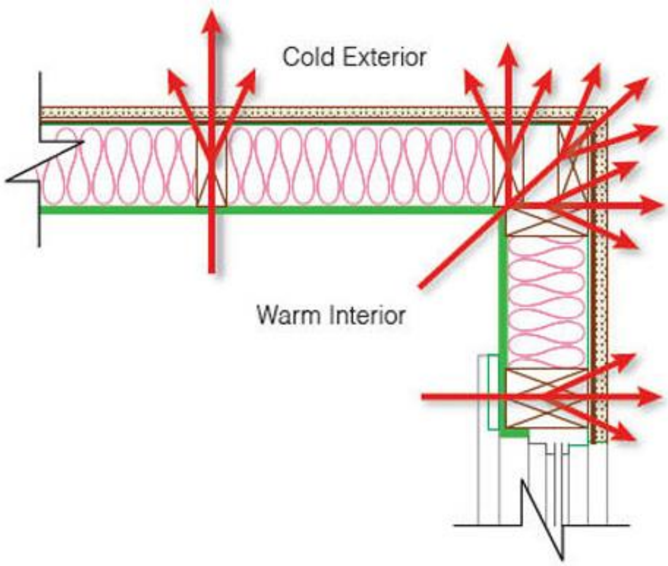

Figure 12. Corners provide a larger surface area through which heat can be transferred. Image: AIA/Architectural Record Continuing Education Program[12]

3.5.3. Specific building components

Each component of a building has specific thermal properties, and consequently, a distinct thermal signature when viewed through a thermal camera. Windows, for instance, are prominent features in many thermal images. This is partly due to the reflective property of glass (section 1.1.2): some of the thermal radiation emanating from a window is actually reflected from nearby sources. Yet, properly insulated windows are a key element to energy efficient building design. Problematic window frame are common, and often require particular attention during inspections.

Other distinctive thermal features include heated floors, fireplaces and electrical systems. Although a complete review of all building components is beyond the scope of this report, a thorough understanding of the function and design of these features is required to interpret thermal images in which they are present.

3.5.4. Difficulties related to outdoor thermography

3.5.4.1. Transient solar heat

Heat transfers that are continuous over time are qualified as being “steady state”. In contrast, temporary heating from the sun is considered to be “transient”. Transient heating is a particular challenge to outdoor thermography, though sharp temperature differentials between the sides of a

[12] https://continuingeducation.bnpmedia.com/course.php?L=38&C=1147&P=5

building can have an impact on indoor thermographic readings as well. South-facing walls, for instance, may be heated by the sun during the day, making them appear badly insulated when viewed through a thermal camera. Transient heat can also linger after the heating source has been removed, with outer walls remaining warm more than an hour after sunset. Transient heating can be further complicated by the shadows cast by nearby objects, which will shift across a building's exterior as the sun moves through the sky. For these reasons, it is advised to perform outdoor thermography shortly before sunrise, when the effects of transient solar heat are minimized.

3.5.4.2. Inclement weather

It is advised to avoid rain, snow, fog or strong winds when acquiring thermal images (section 3.4). As previously discussed, precipitation will dampen the exterior of a building, leading to evaporative cooling. While complete outdoor air stagnation is impossible, the convective heat transfer caused by wind is heavily dependent on its speed. Strong winds will lower the overall temperature of a surface, reducing contrast between adjacent areas and making anomalies more difficult to detect.

3.5.4.3. Surrounding objects

Buildings are generally surrounded by a variety of different objects: neighbouring structures, vegetation, parked cars, clouds in the sky and the ground. These objects will emit and absorb radiation on their own, leading to a radiative exchange with the building. These exchanges can be both substantial and complex, and are influenced by the distance between the objects and the angle at which they face each other. This phenomenon is even applicable to the night sky: the radiative heat loss of a building will be greater after a clear night than a cloudy one. Without consideration of these factors, surfaces which are shielded from night sky or which are adjacent to other heated structures could erroneously be interpreted as having poor thermal insulation.

4. CATALOGUE OF THERMAL CAMERAS

4.1. Selecting a thermal camera

Thermal imaging is a rapidly growing multibillion-dollar industry. Major manufacturers include DRS Technologies Inc., FLIR Systems Inc., the Fluke Corporation, BAE Systems Inc., and the Raytheon Company. This highly competitive market has led to drastic price reductions in thermal imaging equipment over the past few decades, which range from portable handheld devices to sophisticated laboratory equipment. Careful consideration should be given to the device's intended use, as prices vary considerably depending on accompanying software, hardware features and technical specifications. The following section presents some of these key characteristics. Appendix 1 contains a table of handheld thermal cameras designed for building inspections.

4.1.1. Technical specifications

4.1.1.1. Detector resolution

Possibly the most important technical specification of a thermal camera is its resolution. Higher resolutions provide finer details and sharper contrasts, and are particularly important when attempting to view objects at a distance. Thermal cameras have considerably lower resolutions than even consumer-grade visible cameras. While modern smartphones are often equipped with 10 megapixel cameras (3872 x 2592), high-end thermal cameras produce images with resolutions lower than 0.1 megapixels (320 x 240). The resolutions of inexpensive models can be as low as 80 x 60, which may be insufficient for distinguishing fine variations in thermal readings. An important distinction should be made between the detector and display resolutions. Though a high-quality display may be advertised, it will be of little use without a detector capable of capturing images at a correspondingly high resolution.

4.1.1.2. Accuracy VS sensitivity

The accuracy of a thermal imaging system is defined as the margin of error of its readings, and is generally expressed as a percentage (e.g. an accuracy of ±2% will yield a measurement that is within 2% of the target's true temperature). This specification should be distinguished from a device's sensitivity, which is the smallest variation in temperature that it can detect. Sensitivity is given as a change in absolute temperature, generally between 0.05 and 0.15°C for most handheld thermal cameras.

4.1.1.3. Thermal range

A camera's thermal range describes the maximum and minimum temperatures that it can accurately measure. These vary considerably depending on the model, ranging from -40 to 2000°C for portable devices. Thermal cameras designed for building inspections are capable of capturing a much narrower range, generally between -20 to 350°C.

4.1.1.4. Frame rate

As the detector moves from target to target, most modern thermal cameras will continuously refresh the thermal image displayed on its viewing screen. Some models also allow this output to be recorded as a video. A device's frame rate is measured by the number of consecutive images (or frames) that are capture per second. This is often expressed in hertz (Hz), where one Hz is equal to one frame per second.

4.1.2. Hardware features

4.1.2.1. Focus system

As with conventional cameras, a thermal imager's focus is controlled by its lens assembly. Images that are out-of-focus will not only appear blurry, but may also produce inaccurate temperature measurements. Most handheld models use one of three main types of focus systems: fixed, manual or automatic. Fixed systems, which are most common for low-resolution models, will focus on targets at a certain distance from the camera (generally less than one meter) and beyond. High-resolution devices are often equipped with manual focus systems, which allow users to obtain sharper results at a much wider range of distances. However, manual systems require more time and expertise to adjust. Automatic systems can obtain precise focus much more rapidly, although the user will not have the option to choose the target on which to focus.

4.1.2.2. Links to other equipment

Some recent portable thermal camera models have the capability to connect with other devices and equipment. For instance, moisture meters can be linked to thermal cameras to improve temperature readings and increase the device's capacity to detect moisture build-up. Many models are WIFI-enabled, allowing them to upload files and live streams to smartphones, tablets and the internet.

4.1.2.3. Built-in hardware

Common thermal camera add-ons include illuminator lamps and laser pointers, which assist operators in targeting precise locations in darkened areas. Lasers are also sometimes used to measure distances and automatically calibrate focus systems (see section 4.1.2.1). Built-in conventional cameras allow users to simultaneously save visible and thermal images—a particularly useful feature for documentation and post-inspection analysis. Some models equipped with conventional cameras are capable of image fusion, wherein thermal images are overlaid as insets within a larger visible image (Figures 2 and 3).

4.1.3. Software features

4.1.3.1. Onboard software

Thermal cameras are equipped with onboard software that displays images, performs real-time corrections, and allows the user to adjust various settings and parameters. A key onboard software feature is the camera's capability to correct for an object's emissivity coefficient (see section 3.2.3). This allows the incident infrared radiation received by the detector to be converted into a temperature measurement. Some devices provide the option to correct for an object's reflectivity as well.

4.1.3.2. Desktop software

Most manufacturers include software for importing, analyzing and documenting thermal images. The capabilities of these platforms range from performing basic image analysis to applying complex processing algorithms using third-party programs. The format of the exported image files is an important consideration. Though some models output JPEG files that can easily be read by clients and collaborators, others use proprietary file types that can only be viewed and manipulated using accompanying software.

4.1.4. Design

Figure 13. Three different thermal camera designs. Images: FLIR, Fluke[13]

The weight and ergonomics of a device have a non-negligible impact on the comfort of operators using thermal cameras for extended periods of time. Compact designs allow cameras to be stored and carried easily, while durability is important in work environments where devices are susceptible to damage. Operators may find adjustable tilted viewing screens to be convenient. While the settings of some models can be changed using touchscreens, operators wearing work gloves may prefer to scroll through menus using dedicated buttons. Battery life may vary, and some devices include external chargers.

4.1.5. Support

Finally, manufacturers offer a wide variety of client support and services. Due to the high cost of purchasing and repairing thermal cameras, warranties are an important concern when selecting a device. While some companies cover all camera components with a single policy, others split warranties according to housing, batteries and the infrared sensor. Expenses related to periodic calibrations performed by the manufacturer should also be factored into any purchase.

Although this report is meant to cover many basic principles of thermal imaging, in-person training may be required to operate a thermal camera and interpret its readings correctly. Many manufacturers offer various levels of training courses for this purpose, as well as supplemental online documentation and learning material.

[13] http://www.flir.ca/
http://www.fluke.com/

5. THERMAL IMAGING IN ACTION

A wide variety of municipal and community-led initiatives aim to promote energy efficiency in the building sector. These programs focus on either promoting retrofits for existing homes, or helping new buildings meet energy efficient construction standards. To these ends, thermal cameras offer both a valuable diagnostic tool and a compelling means of fostering public engagement. The following section summarizes these programs and presents the results of interviews with their representatives.

5.1. Existing programs

5.1.1. Cool Neighbourhoods

Cool Neighbourhoods is a sustainable development program that supports energy efficiency and conservation in the North Shore municipalities of the Greater Vancouver area. It is an initiative of Cool North Shore, a non-profit organization formed in 2007 that promotes low-carbon communities. Through grassroots engagement, the program encourages homeowners to adopt a variety of energy saving measures, ranging from energy efficient weatherizing and retrofitting to behavioral changes.

The program emerged from a successful project on Eagle Island in West Vancouver that was originally undertaken in partnership with the municipality, BCIT students and the local fire department. Cool North Shore assists interested residents in organizing social gatherings and thermal imaging home visits, which aim to identify areas of heat loss and promote energy efficiency in residential buildings. Participants are provided with information on where energy saving measures can be applied and are encouraged to schedule certified professional audits. Energy audit rebates and government incentive programs are promoted when applicable, and certain homeowners can access discounts on supplies and services that have been negotiated by Cool North Shore.

Figure 14. Cool Neighbourhoods volunteer performs a thermal imaging survey of a house on Bowen Island. Image: Cool Neighbourhoods[14]

Thermal imaging is performed by either local fire departments or by skilled Cool North Shore volunteers. Fire officials may promote fire safety during visits, and in some cases, potential fire hazards such as overheated wiring were discovered. Thermal images stimulate homeowner interest, and are seen as a powerful

[14] http://wwww.coolneighbourhoods.org/cool-neighbourhoods/

communication tool that improves the likelihood of participants following through on post-survey retrofits.

5.1.2. Energy Save New West

Energy Save New West is a community energy program designed to improve energy efficiency and reduce greenhouse gas emissions of residential homes and businesses in the city of New Westminster, BC. The program provides a combination of subsidized energy evaluations, technical support and access to utility rebates and incentives designed to improve the energy performance of existing low-rise single-detached and duplex homes, multi-residential buildings and businesses.

Starting in 2015, the City of New Westminster has supported the design and construction of high performance new homes, by directly engaging local homebuilders and designers in better building practices with respect to air barrier integrity and encouraging advanced thermal envelopes. Energy Save New West currently covers the cost of a plan drawing evaluation, mid-stage (pre-drywall) diagnostic, and final EnerGuide rating for local homebuilders, with access to Energy Advisors who may utilize thermal imaging cameras (in cooler months) during the mid-construction diagnostic to evaluate air barrier weaknesses. When used in combination with a blower door test, thermal imaging cameras are an effective tool to evaluate a home's air tightness and address problems before drywall and cover-up.

5.1.3. Monroe County Energy Challenge

A joint venture between Monroe County and the city of Bloomington, Indiana, the Monroe County Energy Challenge is a program that aims to win a $5 million prize from Georgetown University, awarded to the most effective community-led energy efficiency program. The project fosters community engagement through leadership programs, awareness building and the dissemination of information related to energy efficiency.

Thermal cameras are one of the many tools used by program volunteers to perform basic energy assessments of private residences. When outdoor temperatures are low enough, a combination of outdoor and indoor thermal imaging is involved. While these informal energy assessments are not equivalent to comprehensive energy audits, they are considered to be effective tools for engaging with homeowners. Thermal images are an effective means of capturing homeowners' attention and motivating them to rectify energy loss issues.

5.1.4. Vancouver Thermal Imaging Pilot

The City of Vancouver is currently planning a pilot project to capture outdoor thermal images of between 12,000 and 15,000 single family homes and duplexes. These types of structures are currently responsible for nearly a third of greenhouse gases caused by buildings within Vancouver. City authorities hope that by identifying residences with obvious energy efficiency issues, homeowners can be spurred into retrofitting older buildings and benefiting from energy upgrades. Certain homes may also be inspected using indoor thermography, and willing participants may be eligible for rebates provided by BC Hydro and FortisBC which subsidize the cost of energy retrofits.

5.2. Interviews with representatives of existing programs

During June of 2016, interviews were conducted with officials, volunteers, and representatives of various community and municipal programs that leveraged thermal imaging to promote energy efficiency. Participants are not named in this report. Although interviewees related a wide range of experiences with thermal cameras, the following common themes were identified.

5.2.1. Significant investment of time and money

Thermal cameras are very expensive pieces of equipment. While the initial cost of purchase is substantial, thermal cameras also require regular servicing and repairs. Depending on the intended use of the camera, extensive training may also be needed. While the basic operation of a thermal camera may be grasped by an inexperienced user, substantial knowledge of building construction and the scientific foundations of thermal imaging is needed to perform meaningful diagnostics. The additional costs in terms of time and money incurred by maintenance, repairs and training should be taken into account before purchasing a thermal camera.

5.2.2. Potential for misinterpretation of thermal images

The meaning and significance of thermal images can be easily misunderstood. As detailed in Section 3, a wide range of operational considerations need to be addressed before acquiring and interpreting thermal imagery. The misuse of thermal cameras can lead to the commissioning of unneeded repairs, or conversely, to undetected building issues being neglected. This can expose operators to potentially costly liability issues.

5.2.3. Seasonal limitations

The utility of thermal cameras for building inspections is highly dependent on climate (see Section 3.4). Given the need for a temperature differential between the inside of a building and the outdoors, the time window for effectively acquiring thermal images is limited to the winter months. This timeframe is shorter in the mild climate of the Lower Mainland than in colder parts of the country. Many programs that employ thermal cameras therefore schedule inspections during colder months. This seasonal limitation may affect the feasibility of using thermal cameras during mid-construction phases of new buildings whose construction timelines align with warmer months of the year.

5.2.4. Compelling tool for public engagement

Several interviewees consider thermal cameras to be an effective avenue for fostering public interest in energy efficiency issues. Many community energy programs seek to persuade homeowners to invest in energy efficiency audits, upgrades and retrofits, using motivators such as potential savings and environmental benefits. Though many homeowners are receptive to information on these issues, few are inclined to make significant changes to their behavior or their residences. The strong visual impact of thermal images may increase public buy-in and participation in energy efficiency programs.

6. PROPOSED STRATEGIES FOR THERMAL IMAGING IN SURREY

The variety of existing municipal and community programs reflects the wide range of applicability of thermal imaging in the context of energy efficiency. Based on interviews with the representatives of these programs, as well as consultation with Surrey city personnel, the following four potential programs were considered.

DISCLAIMER

Please note that the anticipated outcomes of the following strategies are based on thermal imaging projects implemented in other cities and municipalities. A complete analysis of the potential costs, benefits and drawbacks of these strategies for the City of Surrey was beyond the scope of this report. It is advised that a thorough feasibility study be conducted before the implementation of any thermal imaging program.

6.1. Promoting thermal imaging as best practice for energy advisors

Energy Advisors (EAs) are experts who are licensed by Natural Resources Canada to conduct energy assessments on buildings. EAs need expertise in a variety of fields, including renovation practices, building science, HVAC systems and computer modeling. They are often contracted to inspect buildings during mid-construction phases, or to assist in retrofitting existing structures. Homeowners and builders wishing to meet the requirements and standards of the EnerGuide Rating System, ENERGY STAR for New Homes and R-2000 housing initiatives must consult with a registered EA. As such, they play a key role in both promoting energy efficiency and enabling energy related rebates and incentives.

EAs may conduct inspections once a building's exterior walls and roof are insulated and the vapour barrier is applied. By identifying air leakages and insulation problems at this stage, builders can address these issues before the installation of drywall. A thermal camera can be used in conjunction with a blower door test for this purpose. As discussed in section 2.2.2, thermal cameras may assist operators in visualizing relatively subtle variations in temperature caused by airflow or missing insulation.

By promoting the use of thermal cameras, the City of Surrey could assist in improving the efficacy of EAs, which in turn will ameliorate the energy efficiency of surveyed buildings. Potential strategies include disseminating educational materials, offering training, and subsidizing the cost of purchasing equipment. This approach would require minimal involvement and investment on behalf of City staff, as the operation and maintenance of thermal cameras would be performed by private contractors.

6.2. Thermal imaging for education on energy efficiency

Several existing energy initiatives leverage thermal imaging as a public outreach tool. While energy efficiency is a common concern among homeowners, many lack the motivation to purchase costly upgrades. This may be partly due to a lack of awareness of the degree of heat loss caused by missing insulation or compromised air barriers. While education on potential financial benefits may incentivise homeowners into investing in energy efficient retrofits, these efforts can be complemented by thermal images. Visual representation can render areas of significant heat loss more tangible to viewers than non-visual information. In this way, thermal cameras can help educate homeowners on heat dynamics and instill an appreciation for energy efficiency issues in their own homes. This approach has been successfully operationalized in the Lower Mainland area by programs such as Cool North Shore.

While private residence retrofits can be promoted by targeting current homeowners, youth-oriented education strategies can foster long-term trends in energy efficiency and conservation. Surrey's Environmental Education Services (EES) program encourages environmental stewardship within K-12 schools by engaging students on topics such as solid waste management and water and energy conservation. Thermal cameras may provide students with an interactive opportunity for learning about both the fundamental physics of heat transfer and building science. By visualizing infrared radiation and understanding its relationship to heat dynamics, students can integrate scientific knowledge with energy conservation issues.

Both of these potential strategies would require the purchase of a thermal camera, as well as assumed maintenance and repair costs. Although operators entrusted with the thermal camera would require some degree of training, the educational objective of this approach would not warrant the same degree of in-depth knowledge of building science as required by exhaustive energy efficiency surveys.

6.3. Thermal imaging for building inspections

6.3.1. Equipping building inspectors with thermal cameras

The recently amended Section 9.36 of the BC Building Code outlines energy efficiency standards, which include requirements for continuous insulation and air barriers. City Building Inspectors are responsible for verifying that newly constructed Part 9 Buildings (houses and small buildings) comply with the BC Building Code.

In the City of Surrey, inspections are carried out at seven stages of the construction process:

1) After the forms of the footings or foundation walls are in place.
2) After the installation of perimeter foundation drain piping.
3) After the preparation of the subgrade.
4) After the installation of chimneys and fireplaces.
5) After the completion of framing, sheathing, exterior doors, windows and the roof membrane.
6) After the installation of insulation and the application of the vapour barrier.
7) A final inspection upon substantial completion, prior to occupancy.

It is after the sixth phase that the integrity of the air barrier can be assessed. Given their utility for detecting air flow and locating missing insulation, thermal cameras could potentially assist building inspectors in this task.

This approach would necessitate a high level of commitment from the City in terms of time and budget. Multiple thermal cameras would be required, and inspectors would need a high level of training in thermal image acquisition and analysis. Liability issues relating to inspections would need to be investigated. Complications due to weather and climate are of particular concern. While a significant amount of new buildings are constructed during the summer months, the effective use of thermal cameras is limited to periods of cold weather (section 3.4).

6.3.2. Thermal imaging for identifying common inspection issues

While environmental factors may prevent the year-round usage of thermal cameras for mid-construction building inspections, thermal images may still be used to improve the inspection process. By surveying newly constructed residences, thermal cameras can identify common energy efficiency issues. Energy assessments could be performed on a sample of new buildings, with the resulting data being compiled by building type and by geographical area. By reviewing this information, inspectors may identify common problem areas on which to focus future inspections.

This approach would require cooperation and coordination with building inspectors, as well as flexibility in scheduling building visits. The window of opportunity for performing energy assessments would be after insulation is installed but before a building is occupied, which can be as little as a few days. Otherwise, post-occupancy visits would require amendments to the City of Surrey's Building Bylaws. Furthermore, to be given access to buildings, the operators of thermal cameras would need to be accompanied by inspectors, whose daily schedules can be unpredictable.

The acquisition and analysis of thermal images would be either performed by City staff or by an external contractor. If employing City staff, the costs, training requirements and liability issues discussed in section 6.3.1 would apply. Data curation should also be considered, as information collected by City authorities is subject to the *Freedom of Information and Protection of Privacy Act* of British Columbia.

PROPOSED STRATEGIES

The following table summarize the target audience, goal, targeted building type and relative cost for each proposed thermal imaging strategy.

STRATEGY	TARGET AUDIENCE	GOAL	BUILDING TYPE	COST
Promoting thermal imaging as best practice to energy advisors	Energy advisors	Ameliorating energy advisor performance	Occupied and/or newly constructed	Low
Thermal imaging for education on energy efficiency	Homeowners and/or K-12 students	Educating the public on the benefits of energy efficiency	Occupied residence	Medium
Equipping building inspectors with thermal cameras	Building inspectors	Providing new tools to building inspectors	Newly constructed	High
Thermal imaging for identifying common inspection issues	Building inspectors	Improving the building inspection process	Newly constructed	High

6.4. Future steps

In addition to a more complete cost-benefit analysis of the proposed programs, it is advised that City managers investigate the legal implications of the following:

- Potential liability risks involved in data collection.
- *Freedom of information* implications of storing address-specific information on energy efficiency.
- Building access permissions for external consultants and for city staff who are not inspectors.
- City bylaws that may require amendments to allow the implementation of the aforementioned programs.

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APPENDIX 1: HANDHELD THERMAL CAMERAS DESIGNED FOR BUILDING INSPECTIONS

MODEL			TECHNICAL SPECIFICATIONS					HARDWARE					SOFTWARE		DESIGN		COST (CDN)
Photo	Number	Manufacturer	Detector Resolution*	Temperature range	Accuracy	Sensitivity	Framerate	Focus system	Digital camera resolution (megapixels)	Laser Pointer	Lamp	WIFI	Image format	Emissivity correction	Weight	Battery life	
	U5855A	KeySight	160 x 120	-20 to 350°C	±2°C	0.10°C	9 Hz	Manual	3.1	Yes	Yes	No	JPEG	Yes	746 g	4 h	4,253.00
	C2	FLIR	80 x 60	-10 to 150°C	±2°C	0.10°C	9 Hz	Auto	0.3	No	Yes	No	JPEG	Yes	130 g	2 h	899.00
	E4	FLIR	80 x 60	-20 to 250°C	±2°C	0.15°C	9 Hz	Auto	0.3	No	Yes	No	JPEG	Yes	575 g	4 h	1,325.00
	E5	FLIR	120 × 90	-20 to 250°C	±2°C	0.10°C	9 Hz	Auto	0.3	No	Yes	No	JPEG	Yes	575 g	4 h	1,990.00
	E6	FLIR	160 x 120	-20 to 250°C	±2°C	0.06°C	9 Hz	Auto	0.3	No	Yes	No	JPEG	Yes	575 g	4 h	3,320.00
	E8	FLIR	320 x 240	-20 to 250°C	±2°C	0.06°C	9 Hz	Auto	0.3	No	Yes	No	JPEG	Yes	575 g	4 h	4,995.00
	E40bx	FLIR	160 x 120	-20 to 120°C	±2°C	0.045°C	60 Hz	Manual	3.1	Yes	Yes	Yes	JPEG	Yes	869 g	4 h	5,195.00
	E50bx	FLIR	240 × 180	-20 to 120°C	±2°C	0.045°C	60 Hz	Manual	3.1	Yes	Yes	Yes	JPEG	Yes	869 g	4 h	7,975.00
	E60bx	FLIR	320 × 240	-20 to 120°C	±2°C	0.045°C	60 Hz	Manual	3.1	Yes	Yes	Yes	JPEG	Yes	869 g	4 h	9,300.00
	T420bx	FLIR	320 × 240	-20 to 120°C	±2°C	0.030°C	60 Hz	Auto/ manual	3.1	Yes	Yes	Yes	JPEG	Yes	855 g	4 h	11,640.00
	IR0002	PerfectPrime	60 x 60	-20 to 300°C	±2°C	0.15°C	6 Hz	Fixed	0.3	No	Yes	No	BMP	Yes	320 g	6 h	449.00
	Reveal	Seek	206 x 156	-40 to 330°C	±5°C	0.10°C	9 Hz	Fixed	None	No	Yes	No	PNG	No	117 g	10 h	512.41
	TiS20	Fluke	120 x 90	-20 to 350°C	±2°C	0.10°C	9 Hz	Fixed	5.0	No	Yes	Yes	JPEG, BMP, IS2	Yes	720 g	4 h	2,195.00
	TiS40	Fluke	160 x 120	-20 to 350°C	±2°C	0.09°C	9 Hz	Fixed	5.0	No	Yes	Yes	JPEG, BMP, IS2	Yes	720 g	4 h	3,995.00
	TiS50	Fluke	220 x 165	-20 to 450°C	±2°C	0.08°C	9 Hz	Fixed	5.0	Yes	Yes	Yes	JPEG, BMP, IS2	Yes	720 g	4 h	4,995.00

* Given in number of columns and rows of pixels.

APPENDIX 2: QUESTIONNAIRE REGARDING THERMAL IMAGING PROGRAMS IN OTHER MUNICIPALITIES

1. Greetings

Personal introduction

Name of interviewer (Andrew Plowright)
Explain role as student researcher (supervisor: Rory Tooke, community energy planner at the City of Surrey)
Mention of UBC Sustainability Scholars program

Goals of interview

Explain Surrey's interest in thermal imaging
Expected duration of the interview (30 minutes)
Inform that names and organizations will not be attributed to comments
Confirm willingness to participate
Describe a brief outline of the interview

2. Synopsis of thermal imaging program

Unstructured description of program

"Could you give me an overview of the thermal imaging program with which you were involved?"

Origin of the program

"Under the purview of what type of organization was this program undertaken? (Municipal government, community organization, consulting firm, etc.)
"What triggered this organization's interest in thermal imaging?"
"What were your goals in implementing this program?"
"What benefits did you expect?"

Structure

"Were you in charge of this program?"
"Who else was involved?"
"Was this program advertised to the public or to any other type of organization?"

3. Technical considerations

Device users

"Who used the thermal imaging devices?"
"Did the users receive training? If so, by whom?"
"Did the users feel confident in their capacity to operate the device and interpret its results?"

Equipment

"What thermal imaging devices did you purchase? What brand, model, how many?"
"Did you negotiate any discounts?"
"How satisfied are you with these devices?"
"What are some advantages/disadvantages of the devices you purchased?"

"Has the manufacturer provided satisfactory customer service?"

Day-to-day usage

"What is the primary use of your thermal imagers?" (i.e.: detecting heat loss, moisture, etc.)
"At what stage of the building process does thermal imaging occur?" (i.e.: during or after construction)
"At what time of day and during and what period of the year does thermal imaging occur?" (i.e.: mornings, evenings, winter, summer, etc.)

Technical issues

"What technical challenges have you dealt with?"
"Were these linked to improperly functioning devices? Difficulty in interpreting images? Improperly trained personnel?"

4. Conclusions

Program results

"What have been the program's greatest successes? What has it failed to accomplish?"
"Do you feel that it has achieved the goals that were initially outlined?"
"Has thermal imaging had an impact on the energy efficiency of buildings in your municipality?"
"What ongoing challenges are your trying to address?"

Recommendations

"Would you recommend thermal imaging devices to other municipalities?"
"What advice would you give for the successful implementation of a thermal imaging program?"

5. Wrap up

Other contacts

"Can you recommend other contacts with relevant experiences?"
"Would you be willing to share their contact details?"

Follow-up

"The information gleaned from this interview will be synthesized into a report for the City of Surrey. Would you be interested in receiving a copy?"

Thank you!