A brief history of Thermosense

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ABSTRACT

This paper briefly discusses the history of the Thermosense conference.

The first Thermosense Conference held at the Chattanooga Choo-Choo Hotel in 1978 was in response to the "Carter Energy Crisis". There were three sessions with a total of fifteen papers presented. The sessions all dealt with IR thermography with the first devoted to building heat loss, the second giving case studies and the third devoted to progress, pitfalls and potentials. There was also a poster session. Thermosense was sponsored initially by eight organizations. SPIE now sponsors Thermosense.

The conference was dubbed "Thermosense" by one of the founders, Tom Lillesand, who, along with the other two founders, Alan Stevens and Bob Madding, organized and chaired the conference. About 200 people attended Thermosense I. Initially, Thermosense was completely focused on energy conservation in buildings. As IR technology evolved, applications were developed in numerous different areas. The current focus of IR thermography applications at Thermosense is primarily in the areas of maintenance diagnostics, building science, research and development, non-destructive testing and manufacturing processes.
The application of IR thermography technology has also evolved with sophisticated data analysis systems and data acquisition systems, e.g. drones. Plus, more applications are being automated. The user base has expanded tremendously as the technology evolves making IR cameras easier to use and less costly.

INTRODUCTION

Thermosense was born in 1978 as a result of the first oil crisis that began in 1973. The Organization of Arab Petroleum Exporting Countries embargoed several countries including the United States it perceived as supporting Israel during the Yom Kippur War[1]. The price of a barrel of oil roughly quadrupled from 1972 to 1975 throwing many countries into an energy crisis.

With inexpensive energy we as a nation didn't concern ourselves greatly with energy conservation. We built many residential buildings with the erroneous concept that "heat rises" so all we needed to do was put a blanket of insulation in the attic. We didn't worry about gasoline mileage of our vehicles, as gasoline was cheap.

The first oil crisis changed all that. Price controls were implemented that limited the price increase of "old oil". This exacerbated the crisis. Also, alternative energy research was discouraged with the intention of increasing oil exploration[1].

Results of this crisis include highly improved building construction design for energy conservation. Smaller, more efficient cars became the norm. Alternative energy research and development eventually commenced. The Department of Energy was formed in 1977. And IR imaging and IR thermography began to be seen as valuable tools for building energy surveys.

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IR imaging also played another role in the energy crisis. From Herb Kaplan, exhibits chair at Thermosense I and an early author and strong promoter of the Thermosense Conference: "I do recall my New Jersey "sneak attack", but I'm not certain about the exact dates. Soon after the gas shortage was announced and the price went up over a dollar, I was heading south on the Jersey Pike with an IR camera and stopped to sneak a scan of a fuel tank farm. Almost all the tank IR images showed near full and, shortly thereafter, an article appeared in the news claiming that there was plenty of gasoline at the inflated price but not at the old price." Herb's last comment probably refers to the price controls of old oil.

One thing we learned is people respond to increased prices. If it is less expensive to insulate one's home than to pay increased fuel prices, we'll do it, especially, if the payback is short term. Convincing people of this, however, is not always easy. And we made mistakes. Unscrupulous insulation contractors often did a poor job of retrofitting insulation especially exterior walls, as quality control was problematic. IR imaging in the hands of a qualified person, however, could do a great job of evaluating the quality. The problem was the consumer didn't know about IR imaging and many (most?) insulation contractors wanted nothing to do with it. "You mean I might have to go back and fix it?"

Counter to that modus operandi, one family comes to mind, Lee Allen and his daughter, Sharon. Comments from Sharon, "My father was first introduced to IR through research work he did with Princeton University. He was the insulation contractor on the project. Once he saw the infrared, he had to have one. In 1979 he purchased his first Inframetrics 525 and started doing IR quality control of his own work. I came to work for him in 1981. Soon, the oil crisis was over and people no longer cared about how much it cost to heat their homes and the insulation work started to taper off. We started learning about the use of IR in electrical (my father was an electrician) and roof moisture inspections. In 1984, it was decided I should start AAIT (Allen Applied Infrared Technology) and have it be a woman owned business. A few years later, my folks moved south, and he became, what we referred to as, AAIT South.

Your comment about unscrupulous contractors... They were out there and did partial jobs. I remember performing an IR quality control inspection on a house my father had bid on, but the homeowner went with the lower bid contractor. As I looked around at the walls, I told the homeowner he got just what he paid for, 2/3 of a job. The homeowner then hired my father to correct the installation. The follow up IR quality control proved my father's efficiency. Pop was never one to criticize other people's work. He would refer to it as 'casual'."

Sharon and Lee contributed seven papers to the Thermosense Conferences, the first in 1983, the last in 1996. Sharon and her husband ran the business for many years, and now have recently retired.

The second oil crisis began in 1979 as a result of the Iranian revolution. Crude oil prices doubled over the next year, resulting again in shortages with long gasoline lines, again.

THERMOSENSE INCEPTION

It only took one oil crisis to begin Thermosense. The timing was good as infrared imaging radiometers were just reaching the commercial market. By today's standards we would think of them as heavy, expensive and operationally difficult. As late as the early 1980's it could take minutes with charts and graphs to obtain a temperature. Image quality wasn't great either. The detector for most of these IR cameras was cooled with liquid nitrogen. Even with these disadvantages IR thermographers did a lot of good work and developed many great applications.

Because it could detect heat loss, IR thermography was utilized by many agencies to publicize and document energy waste. Entrepreneurial thermographers "sprang out of the woodwork." Many early thermographers were very conscientious, but they made errors due to a lack of understanding. Unfortunately, there were also those who either didn't care, or thought they didn't need a thorough understanding of thermography. As a result, in the late 70's, thermography was frequently misused. The Thermosense conference was started out of necessity to provide a forum for the sharing of information, ideas, procedures, and standards.

Tom Lillesand, Al Stevens and Bob Madding, all graduates of the University of Wisconsin, Madison, were the initiators of the Thermosense Conference in a bar in DuPont Circle, Washington, DC while attending the annual American Society of Photogrammetry meeting in 1977. When the first Thermosense was held in September 1978 at the Chattanooga
Choo-Choo Hotel in Chattanooga, TN, Tom had joined the faculty at the State University of New York College of Environmental Science and Forestry (SUNY-CESF) in Syracuse, New York. Alan was working for TVA in Chattanooga and Bob was on the faculty of the University of Wisconsin-Extension (UWEX).

Right after Thermosense I, Alan took a job with US Geological Survey in Reston, VA. Bob stayed at UWEX for four years running short courses in IR thermography and helping develop the first energy audit program. He then joined Inframetrics and has focused on IR thermography applications since[2].

Tom remained at SUNY-CESF through 1978. A major emphasis of Tom's research agenda there was remote sensing of water quality in the St. Lawrence Seaway and Onondaga Lake in Syracuse. He had the good fortune to be able to access airborne thermal IR imagery from the USAF Rome Air Development in support of this research. The data were invaluable in the detection of pollution sources, from oil slicks, to industrial waste outfalls. It was also clear that monitoring building heat loss using thermal IR imagery was low hanging technical fruit. Hence his interest in spreading this word. He had been a student member in American Society for Photogrammetry and Remote Sensing (ASPRS) since 1969 and a regular professional member upon completion of graduate school in 1973. He believed ASPRS had both the ability and obligation to help spread the word on airborne and terrestrial thermal sensing in a range of applications. Eventually Tom joined the faculty at the University of Wisconsin-Madison and retired from there in 2006.

Thermosense I was heavily supported by the US Department of Energy. Herb Kaplan, then with Barnes Engineering, was the exhibits chair. About 180 people attended the first Thermosense. Many were DOE employees. Our country was in the midst of an energy crisis at that time, and the early Thermosense conferences dealt heavily with building envelope and building integrity IR studies. A total of 15 papers were presented at Thermosense I.

American Society of Photogrammetry (ASP), Department of Energy (DOE) and the Tennessee Valley Authority (TVA) in cooperation with the Environmental Research Institute of Michigan (ERIM), American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE), the Mid South Region of ASP, the Society of Photographic Scientists and Engineers and Society of Photo-Optical Instrumentation Engineers (SPIE) sponsored Thermosense initially.

And it is important to note that Thermosense is a very international conference with many attendees, authors and steering committee members from other countries. Their participation has helped make Thermosense important throughout the world. We have steering committee members from Argentina, Canada, Finland, France, Germany, Italy, Japan, Norway, Poland, Russia, Sweden and the USA. And we have had authors from many additional countries including Australia, Austria, Belgium, Brazil, China, Chile, Croatia, Czech Republic, Denmark, Estonia, Greece, Iceland, India, Korea, Latvia, Malaysia, Mexico, Spain, Switzerland, Taiwan, UK and Venezuela. Participants represent USA and foreign government agencies, universities, research centers, equipment manufacturers, IR training groups, contractors, and individual IR practitioners.

In late 1979, at the direction of the Steering Committee, Herb Kaplan met with Sue Davis of SPIE, in pursuit of a broader venue for Thermosense. Joe Yaver, SPIE's Executive Director, made us an outstanding offer and, as a result, subsequent Thermosense conferences were held under the aegis of SPIE, and the Thermosense membership was accepted as a new SPIE Working Group. As predicted, applications broadened rapidly and, by 1982, Thermosense V featured full sessions devoted to Predictive Maintenance, Process Monitoring and Future Trends as well as the then traditional Building and Structures applications. Adapting readily to the new thrusts of the market for IR sensing instruments, the Steering Committee abandoned the "Fall Meeting, Heating Season" concept, seeking, instead, a broader audience and participation. Thermosense was not held in the fall of 1986 but, in the spring of 1987, Thermosense IX was integrated into SPIE's AeroSense International Conference and Exhibit, and held in Orlando, Florida. It remains to this day a part of **SPIE Defense + Commercial Sensing**, an annual spring event. SPIE is now the International Society for Optics and Photonics.

Conference Proceedings were not published until after the conference prior to 1987. That year's conference chair, Bob Madding, convinced the Steering Committee that we could get the papers in and the proceedings published in time to be available at the conference. Now the papers are made available through the SPIE online digital library.

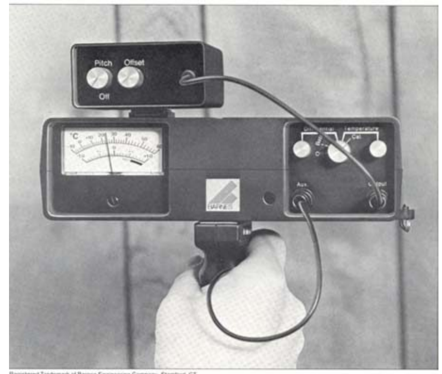
EVOLUTION OF IR INSTRUMENTATION

How it was in 1978: Typical Instruments

Infrared sensing instruments are traditionally classified into three groups: point-sensing, line-scanning and thermographic (two-dimensional scanning). Point-sensing devices (commonly called Infrared Radiation Thermometers) collect radiant energy from a spot or area on the surface of an object to be measured (the target) and provide an output indication, usually in terms of target temperature. Line-scanning instruments provide an output, generally an analog trace, of the radiant energy (or, in ideal cases, temperature) distribution along a single straight-line projection from the target surface. Thermographic instruments (imagers) provide an image of the energy distribution over a scanned area on the target surface. This is presented in the form of an intensity modulated black and white picture or a synthesized color display called a thermogram. In 1978 focal plane array based thermal line scanners and imagers was still an intriguing idea. Typical thermal line scanners and imagers of the time incorporated cooled, single-element detectors and opto-mechanical scanning mechanisms that combined to produce the thermal images. Radiation thermometers were bulkier than today's counterparts but, essentially, the same in configuration. Radiometric imaging software for real-time temperature readout and analysis was not available commercially. Despite these limitations, there were ongoing programs for commercial applications of thermal sensors and imagers, particularly in the area of energy conservation. Since temperature readout of thermograms was not easily attained, the bulk of imaging applications produced qualitative thermograms. We distinguish the quantitative from the qualitative typically by calling the quantitative "Infrared Thermography", sometimes just Thermography and the qualitative "Infrared Imaging".

Aerial thermography applications dealt primarily with housing roof scans. Many of these were community sponsored with DOE funding and/or promoted by local power companies and provided homeowners with images showing comparative energy loss profiles. A typical point sensor featured an aiming sight, a meter (usually analog) reading in temperature units, an emissivity input adjustment and a battery. One very popular exception was the ThermoFlow Energy Meter, produced by Linear Labs. This instrument read out directly in target exitance (watts/cm^2) and came with instructions and charts for converting the readings to insulation R-value. The infrared detector of choice in point sensors was the radiation thermopile.

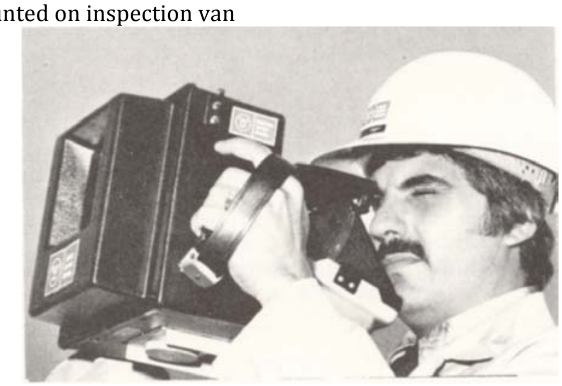
Raytek Raynger radiation thermometers in various configurations



Barnes InstaTherm with sonic peak sensor

AGA Thermovision 650 mounted on inspection van

Hughes Probeye argon gas cooled thermal viewer



Barnes ThermaTrace line scanner

Figure 1 displays photographs of several of the instruments used in commercial applications in 1978 that were presented at Thermosense I.

Typical thermal imagers of the time were the AGA 750, the Inframetrics 510 and the Hughes Probeye. These all featured cryogenically cooled detectors and opto-mechanical scanning mechanisms. Effective temperature measurement was estimated by post processing of the thermograms using look-up charts. The Barnes ThermaTrace offered a single line analog display superimposed over a visible target image with templates provided for estimating the target effective temperature as shown in Figure 2.

Figure 2. ThermaTrace display with vertical line scan superimposed over visible image of stack.

The 1980s, software and portable imagers

The early 1980s marked the introduction of thermal imaging software, the first thermoelectrically cooled portable thermal imager and the first uncooled pyroelectric-vidicon-based thermal imager. The ISI VideoTherm thermal viewer became available around 1980. This was a portable, battery-powered, nonmeasuring TV camera system based on a pyroelectric vidicon (pyrovidicon) tube. The VideoTherm operated in the 8-14 μm spectral region (see figure 3).

Figure 3. VideoTherm pyroelectric vidicon camera with modified videocassette recorder.

AGA Thermovision introduced the AGA 110, manufactured by Magnavox, around 1983. This was a portable, battery-powered, non-measuring imager based on a 48-element thermoelectrically cooled lead selenide linear detector array coupled with an oscillating mirror scanner. The 110 was derived from the AN/PAS series of battlefield viewers developed by Magnavox for the US Army. (See figures 4 and 5).

Figure 4. AN/PAS battlefield thermal viewer.

Figure 5. AGA 110 industrial thermal viewer.

Thermal imager-compatible software was developed by Gesotek (Germany) and Thermoteknix (UK) around 1981 and introduced in 1982 by AGEMA (formerly AGA) to operate with their 780 and 782 thermal imaging systems. The software ("DISCO" and "AIMS") was integrated into a BMC desktop computer/printer and permitted the analysis of images fed by the camera or saved on a modified video recorder. The software featured the first commercially available temperature line scans, histograms and image subtraction capabilities. The integral printer allowed printout of color thermograms. Around 1980 the British introduced a new detector that performed time delay and integration within the detector material itself. The SPRITE (signal processing in the element) detector and its incorporation into a high-resolution thermal imager are reviewed in the Leftwich paper[3] that explains:

"It is possible to manufacture SPRITE detector filaments which are equivalent (depending on the applied field) to about 7 to 14 discrete, high D* elements, thus significantly reducing the number of leads to the cold finger and the complexity of the array."

Figure 6. The Mitsubishi 5120C was the first commercial IRFPA imager.

The first commercial imager series using SPRITE technology was introduced in 1987: the AGEMA model 400 series. One of this series, the 470, was also the first commercially available thermal imager that combined non-cryogenic cooling, color thermal viewing, on board battery, limited on-board diagnostic software and digital image storage on removable media, all in a single, shoulder-mounted unit.

In the mid-1980s detector mosaics or "staring" infrared focal plane arrays (IRFPA) were used successfully for military night vision FLIR (Forward Looking InfraRed) viewers and have since been made widely available for use in commercial thermal imaging instruments. In an IRFPA camera each detector element is assigned one display picture element and mechanical scanning is eliminated altogether. IR Focal plane array radiometers are adaptations of military and aerospace FLIRs, but unlike FLIRs they are designed to measure the apparent temperature at the target surface and to produce quantitative thermograms.

In 1987 Mitsubishi introduced the 5120C, the first commercial IRFPA imager, based on a Stirling cycle-cooled platinum silicide (PtSi) FPA.

The introduction of the Stirling cycle cooler to thermal imaging instruments is noteworthy because it meant that, for the first time, thermographers had a cryogenic detector-cooling system (below 80 Kelvins) that was contained, like a refrigerator, and eliminated the nuisance, hazard and restrictions of refillable liquid nitrogen containers.

Mitsubishi also promised the "imminent" introduction of a real-time temperature measurement capability but, unfortunately, this capability was not realized commercially until the 1990s. The 5120C is shown in figure 6. Meanwhile, Stirling cycle cryogenically cooled, opto-mechanically-scanned quantitative imagers (imaging radiometers) proliferated in the late 1980s. Inframetrics came out with their "Microcooler" line of miniaturized Stirling-cycle coolers that they incorporated into their new imagers.

A real breakthrough in radiometrics was the introduction of the microprocessor based IR scanners. One of the first was the Inframetrics Model 600. This IR camera as shown in figure 7, developed under the engineering directorship of Jay Teich (who later became president of Inframetrics) displayed a temperature on the screen in real time. It internally corrected for target emissivity and reflected apparent temperature. Charts, graphs and external hand-held computers rapidly became a thing of the past. Other vendors rapidly caught up and a new era of quantitative thermography was born. As IR cameras became easier to use, training became even more important. Technical experts were both thrilled and chilled. To quote Bob Madding on using the Model 600 for the first time: "Now it's a lot easier to get the wrong answer." The IR camera gave excellent results, provided the thermographer was smart enough to enter the correct parameter values. This provided strong impetus for better training and certification of IR camera users.

Figure 7. The Inframetrics Model 600 microprocessor based imaging radiometer.

The 1990s—Uncooled focal plane arrays, consumer night vision and the big merger
The early 1990s produced the "universal" software package for thermal imaging diagnostics, the marriage of the laptop computer to portable thermal imagers, refinements to high-density portable image and data storage media and, at long last, the introduction of IRFPA imagers with temperature measurement capabilities.

The late 1990s marked the introduction of uncooled IRFPA imaging radiometers, packaged thermographic report writing software and the first mass-consumer-market thermal imaging product. They also brought a series of mergers and acquisitions that reconfigured the industry.

While, in the '80s, the major manufacturers of thermal imagers produced "proprietary" software packages to operate with their thermal imaging products, the early '90s saw these same manufacturers offer universal packages made to operate in a "Windows" environment. This permitted the powerful combination of the portable imager and the laptop computer to be deployed in many challenging applications, bringing instant data reduction capabilities to the field and the factory floor. A natural step in this evolution was report-writing software that allowed the user to prepare professional looking on-site reports in record time, thus minimizing the interval between problem detection and corrective action.

Stirling cycle coolers were featured in the introduction of the miniaturized Inframetrics InfraCam in 1993, a nonmeasuring IRFPA imager weighing less than 2 lbs. In 1995 the FLIR PRISM and the Inframetrics ThermaCam, the first miniaturized IRFPA thermal imagers with measurement capabilities were introduced, 1 week apart.

The software revolution of the '90s also introduced powerful tools for nondestructive testing of materials. The development of high-speed image processing software provided a technique known as "Time Resolved Infrared Radiometry" (TRIR) or "Thermal Wave Imaging"—more about that later.

Throughout the'90s, development programs at Minneapolis Honeywell and others, sponsored by the US Army Night Vision lab, produced instruments based on uncooled bolometric, ferroelectric and thermoelectric IRFPA detectors.

In 1994 Infrared Solutions, a new company formed by Honeywell retirees, began manufacturing imagers for the commercial market based on this technology. In 1996 they introduced the SnapShot camera, based on a linear thermoelectric array and made to sell for under $10,000. Other low cost line scanners and imagers, based on bolometric FPAs, followed. Meanwhile a division of Texas Instruments (soon to be acquired by Raytheon) was developing a driver's night vision system for the automotive mass market, based on a ferroelectric FPA. This was first made available in1999, as optional equipment on the 2000 model Cadillac Seville. It sold for under $2000.

Two other merger/acquisitions took place in the late 90's; FLIR Systems acquired both AGEMA and Inframetrics, thus integrating the three largest manufacturers of commercial thermal imaging systems under the FLIR banner.

The 1990s ended with compact IRFPA imagers with on-board image storage and diagnostics, not much larger or bulkier than today's camcorders, available to the predictive maintenance troubleshooter and process control engineer.

To Thermosense XL in 2018—QWIP detectors, price reductions, what else is new?
The millennium brought the promise of ever diminishing prices as the demand for instruments continued to grow and applications proliferate. In 2002 the first real-time radiometric infrared camera to break the $15,000 price barrier was introduced. It weighs less than 2.0 lbs.

Quantum well infrared photodetector (QWIP) focal plane arrays had been under development since the mid-90s, and became available on commercial thermal imagers in 1999. These Stirling-cycle-cooled arrays, operating in the 8-9µm spectral range, are ideally suited to special applications involving high-speed phenomena, high thermal sensitivity and processing flexibility at longer wavelengths. Particularly for transient, high-speed thermal recording, the detector of choice has become the gallium arsenide (GaAs) QWIP FPA. Spectral band filtering has made optical gas imaging IR cameras possible with many new applications. IR imaging platforms have also evolved. Uncooled microbolometer formats have shrunk in size significantly since 1999 as shown in Figure 8, right.

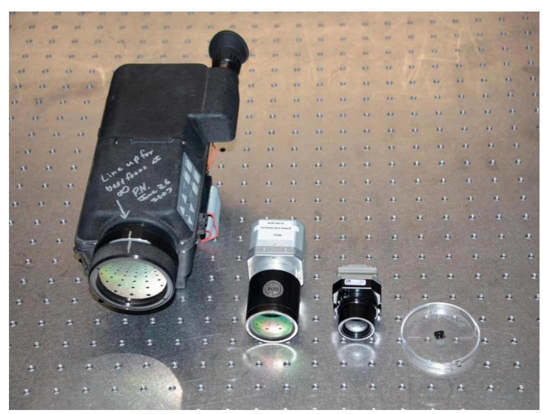


Figure 8. Left, photomontage of some 2000's era thermal imaging instruments including one on a drone. Right, uncooled microbolometer formats have decreased dramatically over time. FLIR cameras are shown from left to right: 1999 (Amber Sentinel), 2006 (FLIR Photon 320), 2013 (FLIR Tau2), and 2016 (FLIR Lepton).

THE EVOLUTION OF APPLICATIONS

There were many ongoing applications for thermal sensing and imaging instruments existing in 1978, but since Thermosense was aimed, initially, at the energy crisis, other applications were not reviewed in the papers of the early Thermosense meetings. It wasn't until the early '80s that Thermosense grew to include other applications.

Applications expansion of the '80—Standards, training and new categories

In 1980, Thermosense III began to reflect the growing awareness of the importance of standards and training—not only in the operation of equipment, but in a clearer understanding of the principals of thermal sensing and imaging and in the interpretation of thermograms. At Thermosense III, a session devoted to Standards and Training represented the first step in this direction. By Thermosense V (1982) sessions were devoted to Building Diagnostics, Plant Facilities, Industrial Applications, Process Control and New Trends. With the addition of the first paper on materials testing in 1983, a conference profile was established that remained constant, with few variations, throughout the '80s and 90's:

- Buildings and Infrastructure
- Predictive Maintenance
- Products and Processes
- Nondestructive Testing and Materials Evaluation
- Research and Development (new trends)

From time to time other sessions were added and subtracted from the conference, reflecting current trends. They have included sessions on electronics diagnostics, night vision, medical and biological applications, and professionalism.

The conference profile continues to evolve with Thermosense XL having additional sessions scheduled on spectral analysis; IRNDT theory, civil structures and applications; and welding/manufacturing.

Buildings and infrastructure applications

Measuring the temperature on the outside of a structure and knowing the thickness and the inside temperature, all under steady state heat flow conditions (often difficult to achieve in the natural environment), permits the determination of thermal resistance (insulating properties). Bob Madding[3] presented a thorough, simplified explanation of heat flow through structures in 1979 at Thermosense II. This served as an excellent primer to this applications category. As Madding points out, however, the measurement of conductive heat flow for insulation assessment is only one factor in practical heat loss (or gain) determination. Some of the other factors are air infiltration and exfiltration, chimney effects, and thermal short circuits or bypasses, which, in many cases, can be serious enough to completely negate the benefits of a retrofit insulation program.

Over the years thermographers have learned to consider the total structure when evaluating the results of thermographic surveys and have learned to recognize and isolate thermal patterns typically associated with airflow as well as those caused by insulation deficiencies.

Driven by the energy crisis of the 1970s, the results of which are still very much with us, infrared aerial scans were instituted by communities and government agencies using adaptations of military aerial thermal mappers. The purpose of these scans was to provide communities, residents and commercial taxpayers with information concerning the heat loss characteristics of their buildings. Although only losses through the roofs were detected, unheated buildings did not register at all, and numerous environmental factors clouded the results, these early

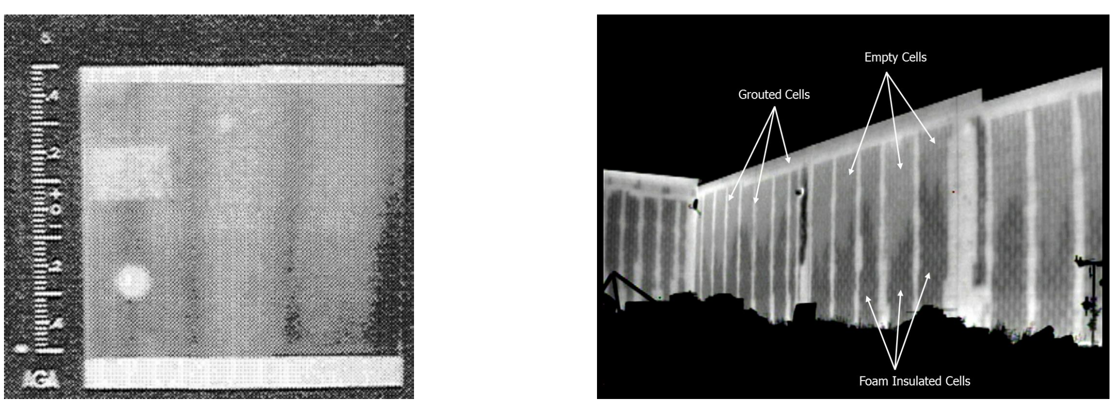


Figure 9. A comparison between an early structural thermogram (left) and a more recent one (right) reported in Thermosense (1980) and Thermosense (2011) respectively.

programs raised community consciousness and identified a new tool for energy conservation. They were also a major driving force in the development of commercially available IR sensing and imaging equipment.

Nationally sponsored and funded building retrofit and "weatherization" programs were put into effect in European countries (Sweden was the first), in Canada and in the US. Infrared thermal sensing and imaging equipment, now developed specifically for the commercial market, was used extensively in these programs, first to assess the retrofit requirements and, subsequently, to check the effectiveness of the work. These were, for the most part, ground-based instruments that provided more comprehensive information about the structures and also provided "ground truth" baselines for the aerial scans. Although priorities have changed, there are still ongoing programs of this kind. In addition, although the initial thrust of these applications was aimed at energy conservation, it soon became apparent that very many other aspects of buildings and structures, such as aging, moisture content and structural integrity could be evaluated using IR sensing and imaging equipment.

Thermographic equipment has been used extensively for the detection of saturated sections of flat industrial roofs since the 1970s. As in most "buildings and infrastructure" applications, these surveys are concerned with detection and identification of thermal patterns rather than quantitative measurements. These patterns are indications of subsurface moisture, and there are two approaches to making these measurements. One depends on solar heating (insolation). The other approach, taken when there has not been adequate insolation, requires that there be a minimum of 10°C difference between interior and exterior surface temperature for at least 24 hours prior to the survey. Both are conducted at night with all surfaces clean and dry and in the absence of high winds (no greater than 15 mph).

When there has been adequate solar heating of the roof during the day prior to the survey, thermal energy is stored in the roof. The saturated sections have higher thermal capacity than the dry sections and, therefore, store more heat. At night, the roof radiates thermal energy to the cold sky. At some time during the night, the dry sections have expended all their stored heat but the saturated sections continue to radiate. When this occurs the thermographer can easily locate and identify the saturated sections. Particularly if there is no temperature difference between the building's interior and exterior, this approach is relatively free of thermal artifacts due to vent pipes, exhaust fans, etc.

The second approach is based on heat loss rather than solar gain. The saturated roof sections are better heat conductors (poorer insulators) than the dry sections. The temperature difference between the interior and exterior will cause heat to flow more through the wet sections than the dry sections. Consequently, warmer areas on the exterior surface indicate water saturation. Of course, since there is a temperature differential between the interior and exterior, this approach is more subject to artifacts caused by airflow and thermal conduction through the roof.

The appearance of the thermograms is otherwise quite similar.

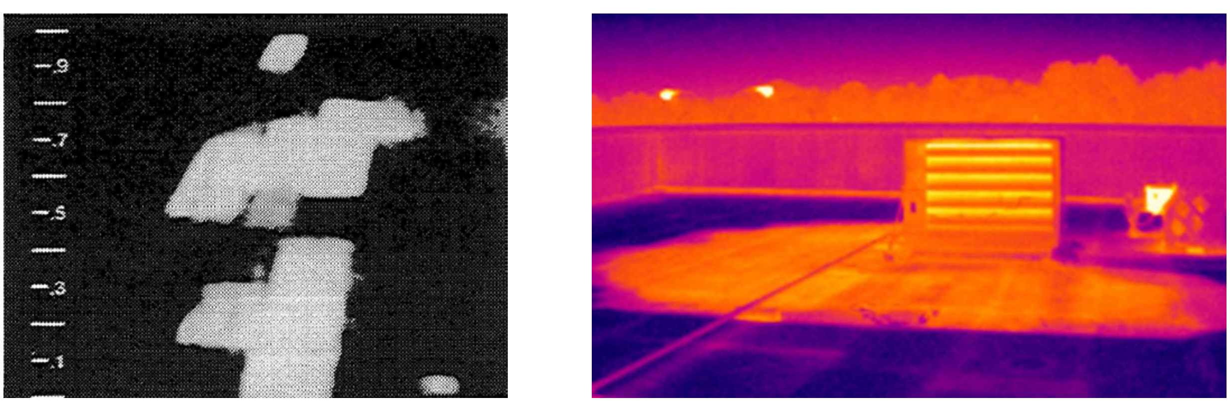


Figure 10. A comparison between an early roof study (left) and a more recent one (right) reported in Thermosense (1980) and Thermosense (2013) respectively.

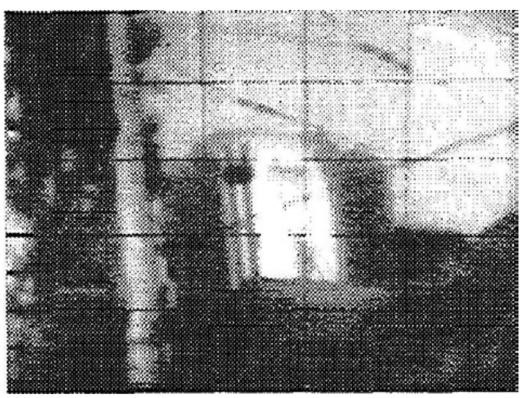
Although structure and roof scan applications have been classified, for years, in the "Buildings and Infrastructure" category, they could just as well be considered as examples of Materials NDT" studies, in that the heat flow principals involved are identical.

Predictive maintenance applications
The use of thermal sensing and imaging in plant condition monitoring and predictive maintenance (PdM), is probably the most widespread of all current applications. From periodic spot checks of bearing temperatures on rotating machinery to fully documented facility-wide programs of predictive maintenance, condition monitoring accounts for the deployment of more thermographic equipment than any other commercial use. The basis for these programs is the fact that erratic or deviant thermal behavior of operating equipment is generally a precursor to costly and inefficient operation and then to failure.

The use of infrared thermal viewers and imagers for plant condition monitoring and field predictive maintenance has grown over the past forty years to where it is a universally accepted adjunct to power facility operation.

Thermographic data from hundreds of power line surveys have been collected and standards have been developed for the thermal behavior of electrical switchgear and electrical distribution equipment. Utilities such as Connecticut's Northeast Utilities Service Company maintain full-time staffs that perform continuing infrared survey work, saving millions of dollars annually in equipment and downtime. Some years ago the Ontario Hydro Corporation launched a new kind of thermographic survey van in whose data banks were stored standard thermal signatures of hundreds of typical disconnects, transformers, power panels and other switchgear. This allows rapid and accurate operator assessment of equipment condition and leads to timely correction of incipient trouble spots.

The first three Thermosense PdM papers were part of the Industrial Applications session at Thermosense IV (1981) and sessions devoted to PdM applications have appeared in every Thermosense since.



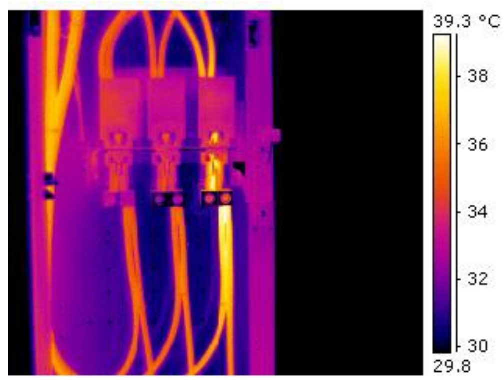


Figure 11. A comparison between an early PdM application thermogram (left) and a more recent one (right) reported in Thermosense (1982) and Thermosense (2016) respectively.

NFPA (National Fire Protection Association) developed a standard NFPA 70E, Standard for Electrical Safety in the Workplace that deals with safety and protection against electrical shock and arc flash, both of which can severely injure or kill workers around live electrical equipment. NFPA 70E first appeared in 2004 and the most recent as of this writing is 2018. Anyone doing IR surveys of electrical equipment should take the NFPA 70E course and adhere to its recommended practices.

There are other standards and certifications for IR thermographers covered in a later section.

Products and processes applications
The early emphasis on energy conservation applications was not the only reason that papers on product and process monitoring and control applications were absent from the early Thermosense conferences. Commercial users were understandably reluctant to share the methods and results of successful applications with a world

filled with potential competitors. Even today, it remains difficult to persuade manufacturers to reveal this kind of information.

As early as the mid-1960s, companies such as du Pont and General Electric were using IR sensors to monitor glass and thin film plastic manufacturing processes. The first Thermosense coverage in this area, however, came in Thermosense V in 1982, with a 6-paper session on "Industrial Processing". In 1984, a tutorial paper by Bob Madding[4] recognized the importance of these applications and served thereafter as a primer on the subject. Madding introduced and illustrated the terms "monitor", "open loop control" and "closed loop control" to the potential user.

Typically, the decision to control a process is not made until a simple infrared sensor is deployed and data are gathered over a period of operating time, under a variety of expected operating conditions and at different points in the process. The condition (quality, consistency, etc.) of the product is correlated to the temperature variations experienced at the various monitored locations. The point (or points) in the process where temperature behavior is most closely related to product condition is selected as the permanent monitoring/control site (or sites). Variations in signal at this site are used to control the process. This can be done manually, with an observer maintaining the temperature readings within allowable limits by manually turning the process on and off or by adjusting the process driving control (gas valve, heater current, speed adjustment, etc.). The ultimate goal, in most cases, is to close the loop by means of a computer/data processor for automatic control of the process.

The first three Thermosense Process Monitoring papers were part of the Industrial Applications session at Thermosense V (1982) and sessions devoted to products and processes applications have appeared in every Thermosense since. The earliest papers discussed steel, glass and automotive process mold temperatures.

Subsequent papers dealt with brake systems and printed wiring. Ultimately, electronics product inspections applications grew until, in 1987 and 1988, VIII and IX had entire sessions devoted to "Electronics and Microelectronics Diagnostics".

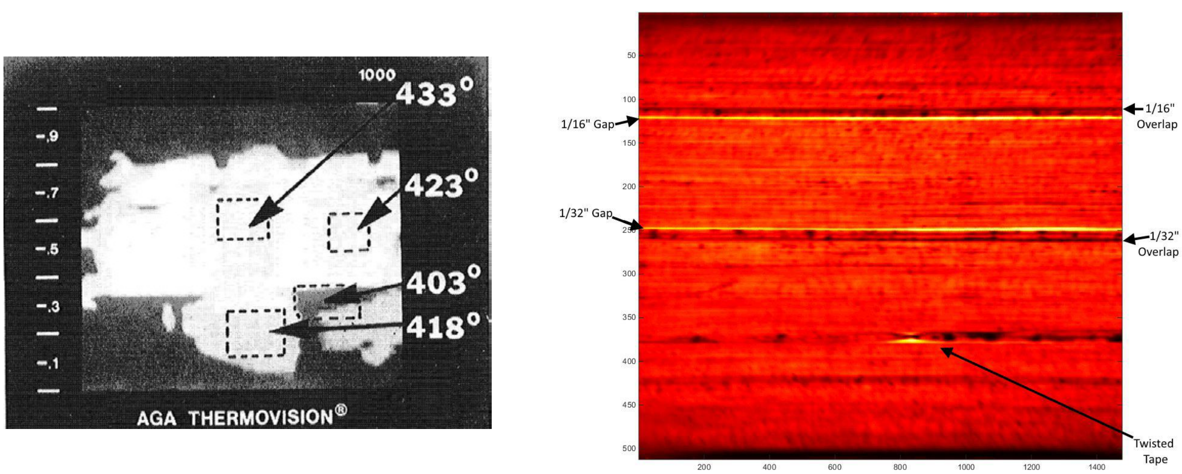


Figure 12. A comparison between an early "Products and Processes" application thermogram (left) and a more recent one (right) reported in Thermosense (1982) and Thermosense (2016) respectively.

Nondestructive testing and material evaluation applications

Infrared nondestructive testing (IRNDT) of laminar materials is based on the facts that a good structural continuity invariably provides good thermal continuity, and that voids, disbonds and foreign matter affect the flow of thermal energy across (normal to) the laminar layers. A passive measurement approach is taken in the establishment of standard patterns when products are being evaluated during normal operation or during manufacture, and the process being monitored produces, or can be made to produce, the desired characteristic thermal pattern on the product surface. Building thermograms are examples of passive nondestructive testing—the heat flow from the inside of the structures to the outside is part of normal operation. When this cannot be made to occur, or when the products or materials are to be evaluated after manufacture, an active, or "thermal injection," approach is necessary.

The thermal injection approach requires the generation of a controlled flow of thermal energy across the laminar structure of the sample material under test, thermographic monitoring of one of the surfaces (or sometimes both) of the sample and the search for the anomalies in the thermal patterns so produced that will indicate a "defect" in accordance with established accept-reject criteria. The equipment necessary, therefore, to perform IRNDT must include not only thermographic scanning instrumentation, but also the means to handle the test samples and to generate and control the injection of thermal energy into the samples.

Within the last several years, innovative approaches to heat injection such as thermal pulse and thermal wave propagation have resulted in improved capability for detecting and assessing small and buried flaws. These, coupled with improvements in computer enhancement methods and availability of high-speed (QWIP-based) FPA imagers, with frame rates up to 900Hz, have had an important effect on image understanding and flaw recognition. Time resolved infrared radiometry (TRIR), also known as thermal wave imaging (TWI) is illustrated in figure 13.

Here, high intensity xenon flash lamps are used to irradiate the target surface with short duration pulses of thermal energy, on the order of milliseconds.

While the surface cools, the heat is conducted into the material at a uniform rate until it reaches a thermal barrier or discontinuity, such as a flaw. At this time, the temperature at the surface is lower than that at the flaw site, and a portion of the heat is conducted back to the surface, simulating a thermal "echo." The time it takes from the generation of the pulse to the reheating at the surface, then, is an indication of the depth of the flaw.

The behavior of the thermal energy moving through the material is similar in many ways to that of a wave of energy propagating through the material and being reflected back to the surface. For this reason the term "thermal wave imaging" has been adopted by some thermographers to describe the process. By using diagnostic software to "time gate" the return thermal images, they can estimate the depths of flaws as well as their size and location, often with excellent precision.

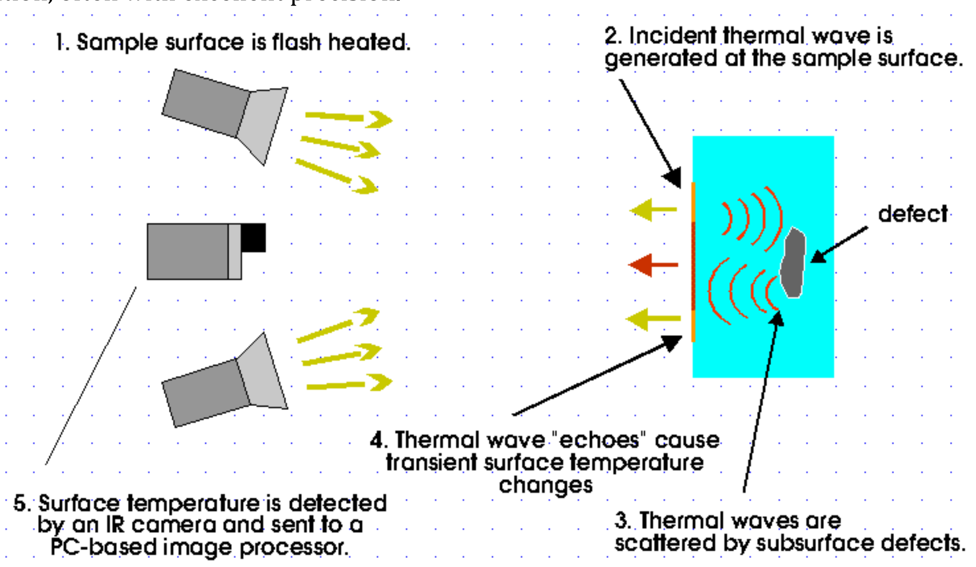


Figure 13. Schematic of basic principle of pulse heating thermographic NDT.

With few exceptions, the new approaches involve the time gating of thermal image sequences following the application of heat, usually a pulse, in order to characterize defects at various depths below the target surface. The term time resolved infrared radiometry (TRIR) is generally used to describe the technique, as illustrated graphically in Figure 14.

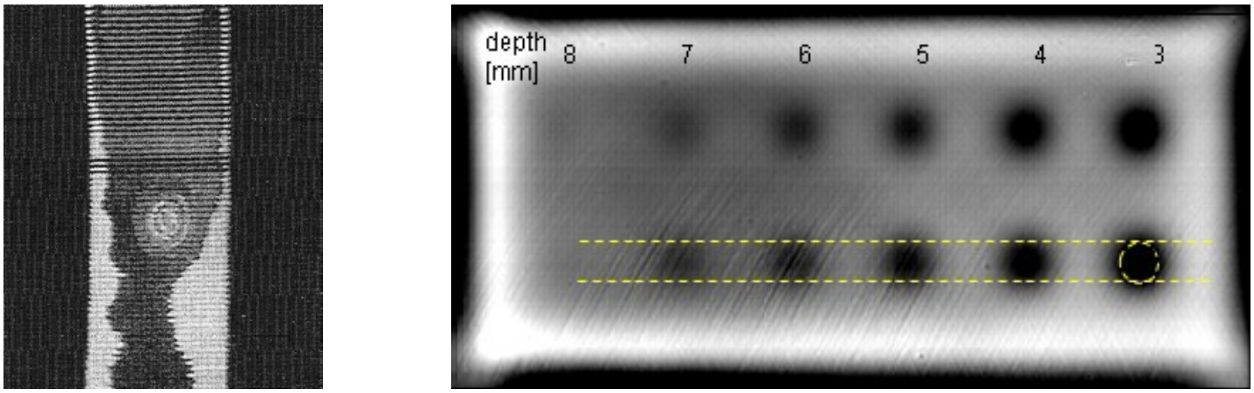


Figure 14. A comparison between an early IRNDT application thermogram (left) and a more recent one (right -thermal signal reconstruction (1st derivative)) reported in Thermosense (1982) and Thermosense (2013) respectively.

Night vision, security and surveillance

The earliest development of thermal infrared imaging systems was based on military requirements for night vision capability. The first night vision devices were of the “star scope” variety, based on radiance amplification or “image enhancement” of available light. Early military “star scopes” used near IR illuminators, which could be detected and so, offered little military advantage. The first truly passive “undetectable” night vision devices operated in the infrared and were based on the detection of thermal radiation from the target surface. For almost half a century, from the introduction of the first thermal IR devices through the current development of uncooled IR focal plane arrays, the military has continued as a driving force in this evolution.

Unlike the needs of most industrial applications, thermal imagers for night vision, security and surveillance applications require no temperature measurement capability. The key requirement here is to present an image of the target with the best possible spatial and thermal resolution, at the greatest possible distance from the target, under the worst conditions of obscuration and absorption in the intervening atmospheric path without the possibility of detection.

Since instruments used for these applications usually need to detect and identify tactical targets through atmosphere in the dark and in bad weather, they operate, generally, in the 8-12 μm spectral window where the atmosphere has very little absorption.
Specific non-military areas of applications include the following:

- Aerial and ground (sea) based search and rescue
- Firefighting
- Space and airborne reconnaissance
- Police surveillance, crime detection and security
- Drivers’ aid night vision

Although many of the instruments used in the earliest Thermosense papers were based on the use of night vision instruments, night vision applications were not included in the conference until Thermosense XII in 2000 with a session on “Airborne and Environmental Applications”.

Figure 15. A typical modern night vision image illustrating the extreme visual clarity routinely attained.

Standards and Certification

More than 30 Thermosense papers have been written over the years relating to standards and certification of IR thermographers. The latest by McIntosh and Huff[5] in 2017 updated us on standards and guidelines relevant to thermographers. IR thermographers especially in predictive or condition-based maintenance should be very familiar with the current standards and certifications including those by ASNT, ASTM, ISO, BINDT and NFPA.

SINCE 1983 MORE NEW AND EXCITING IR CAMERAS—SMALLER IR CAMERAS, OPTICAL GAS IMAGING (OGI) CAMERAS, HIGHER RESOLUTION CAMERAS, DRONE MOUNTED CAMERAS, MORE AUTOMATION AND MORE COMPTETITION

Smaller IR cameras

Prices of IR cameras continue to drop with IR cameras that attach to a smartphone at $400 or even less. Figure 16 shows such an IR camera attached to a smartphone with a camera image and accompanying IR image. Bob Madding took these IR images when looking at purchasing a home that had electric radiant in the ceiling. The real estate agent didn’t know if it functioned and had just turned it on, as the weather was warm at the time of the showing. Bob took several IR images, one of which is shown on the phone and another as a separate IR image.

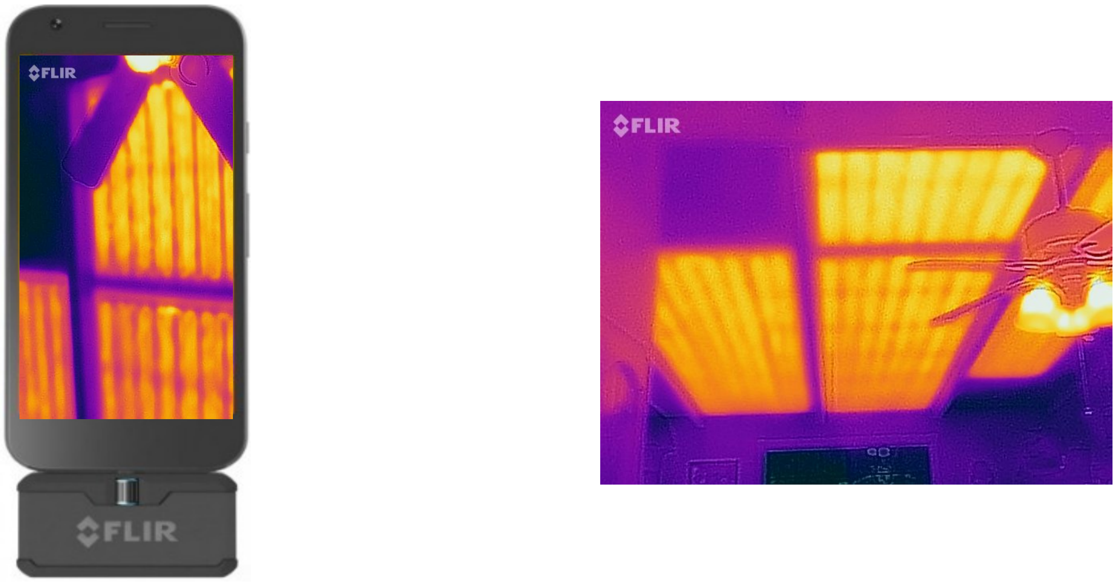


Figure 16. IR camera attached to smartphone, left. IR image of ceiling radiant heat, right.

Optical gas imaging (OGI) cameras
OGI cameras can help detect methane, sulfur hexafluoride, and hundreds of other industrial gases quickly, accurately, and safely—without shutting down systems. With OGI cameras, you can scan broad sections of equipment rapidly and survey areas that are hard to reach with traditional contact measurement tools. OGI cameras can also detect leaks from a safe distance, displaying these invisible gases as clouds of smoke. Figure 17 shows an example of a thermal image of a SF_6 gas leak that cannot be seen by the naked eye.

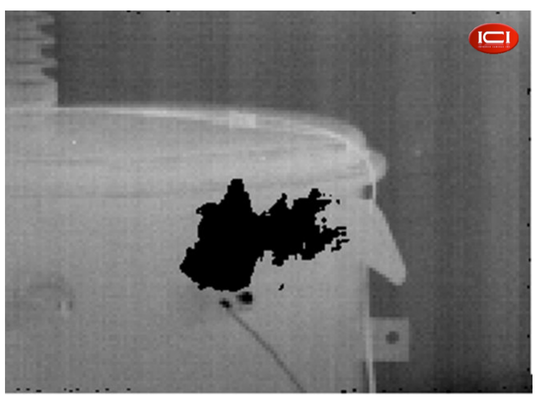


Figure 17. IR image from OGI camera showing SF_6 gas leak invisible to the naked eye.

IR Cameras on Drones
Drones were at first called unmanned air vehicles (UAVs) and developed as early as WWI and WWII for military applications. Both programs were disastrous. But the Germans developed the first unmanned rockets and wreaked havoc with them over England. The US developed a series of cruise missiles in the 1950's. But the military drones of today began being developed in the late 1980's and 1990's. Modern versions have been used extensively by the military since September 11, 2001.

The small commercial drones we use today are very different from military drones. Size, range, cost and payload are four big differences. Many different types of IR cameras can be mounted on drones. Figure 18 shows an airborne IR image of gas leakage near an oil pump. This is one frame of a video as viewing real time or video imagery makes the moving gas plumes much easier to spot.

Figure 18. Airborne IR image of gas leakage from an oil well pump.

Where access may be difficult the drone mounted IR camera can save the day. Bob Madding recalls being in a resort and noticing from the outdoor third floor walkway, a distribution utility pole with lots of electrical connections at his level and just some 30 feet away[2]. He contacted the local salesperson and borrowed an IR camera finding a critical problem on one of the connections. He contacted the local utility and they repaired the problem.

Bob knew this utility had a great IR thermography program and was a bit surprised he found a problem. In talking with their thermographer, he found their big problem was access. They weren't allowed to go to the third floor of the resort. A chain link fence restricting access to a railroad track blocked their approach from the ground. They couldn't see these connections from the ground. A drone mounted IR camera could save the day in examples such as this. We don't see drones doing an entire transmission or distribution systems but they could be invaluable for short range limited access applications. This could include also confirmation of a problem and confirmation of a repair.

A roof moisture IR survey is another application where drones could supplement an airborne flyover, or standalone for just one or two buildings. And they could also survey the sides of buildings where viewing from the ground is difficult. The possibilities are enormous. Just imagine saying "I can put an IR camera over that or beside that."

More Automation Applications

Automation applications have been developed for years, especially after uncooled microbolometer detector array cameras came into being and wireless communications have become commonplace. But now electric power utilities have begun automating diagnostic technologies such as vibration and IR thermography. One utility, Duke Energy has budgeted over $11 million for automating these applications.

As an IR thermographer who has done a fair number of electric substation and switchyard IR surveys, Bob Madding sees pluses and minuses to automation of IR surveys. In addition to looking for problems with the IR camera most IR thermographers also used other senses to listen, smell and look visually for problems. "Hmmm. That patch of oil on the ground wasn't there the last time we did an IR survey." "That's a funny sound. Haven't heard that before. Sounds like frying bacon, only louder." That's some of the bad news.

Other problems may include interpretation such as due to environmental factors. "Is that a problem on phase C oil circuit breaker tank?" "No, that's just solar loading. It happens particularly this time of year." Wind effects need to be accounted for. So, hopefully the automation would include wind speed. And load. We mustn't forget about load. These are just some of the challenges to replacing the IR thermographer with an automated system.

The good news is the IR thermographer can sit in an office and look at the substation on a computer display. It's safer, especially if battery rooms, tunnels and vaults are automated. And automated IR surveys are more thorough giving 24/7 coverage with alarm capability. If you're wondering if a warm circuit breaker tank is due to solar loading, look at the imagery from the night before, providing there's sufficient load.

Return of some application(s)
Herb Kaplan thinks that cost and size reductions with improved IR imagery and display with better user understanding and need could bring back some applications that have been largely abandoned. From Herb: "When IR driver's aid night vision became available options on Cadillac's around 1998, and on BMWs somewhat later, I envisioned a huge potential commercial market for these accessories. The market never seemed to take off, however. My Caddy dealer said it was a combination of MSRP, (cost to the consumer), ignorance on the part of salespeople, and poor profit margin for both the vendor and the auto manufacturer. I felt, at the time, that educating consumers with regard to features and benefits would make big difference.

Today, with manufacturing costs for the basic elements considerably lower, and with improved public familiarity with the technology, I believe there is a new opportunity to revisit this market. The benefits are numerous and easy to explain to consumers."

More Competition
In 2005 Fluke Electronics Corporation bought Infrared Solutions a manufacturer of IR cameras. This acquisition provided Fluke with the technology and resources to develop a broad range of IR cameras.

Other manufacturers include Infrared Cameras Inc., IR Cameras, Xenics and Optris. There are also more smartphone IR camera manufacturers, such as Seek Thermal.

Summary
The authors have been fortunate to work in the IR thermography community for the past 40 years and watch the IR camera technology, applications, training and standards grow significantly.

We wrote in 1983 that the importance of technical and applications as well as training in infrared thermography has never been more crucial than it is today (1983). The new generation of IR cameras, some as small as a flashlight, that cost under $10,000 and provide quantitative temperature readout puts infrared technology in the hands of a whole new category of users. In the early days of infrared thermography, engineering and technical professionals spent almost a week being trained as IR camera operators. It often took 10 or 15 minutes to graphically interpolate a single temperature from the IR image. Microprocessor based IR cameras first introduced in the mid-1980s were the initial breakthrough that accelerated the importance of quality IR training as well as infrared conferences. With the new generation of small, low cost, quantitative IR cameras, users can learn to operate them in about 30 minutes, considerably less than almost a week.

IR camera operation and report generation have been greatly simplified. Madding remembers taking about the same time to generate an IR report that it did in acquiring the imagery. Spend 4 days collecting data, spend 4 days generating a report. Now report creation days have turned into hours. Some thermographers generate their PdM reports after a survey prior to departing. And with wireless technology communicating their results has never been easier.

In 2018 we have IR cameras for $400 or less that can attach to a smartphone. No training required to operate; however, training is required to become a proficient IR thermographer, most of whom would have a much higher end IR camera for their work.

The ease of getting temperature readouts has led to a multitude of interpretation errors by the untrained user. As IR cameras do not read temperature directly, but must calculate it from knowledge of other parameters such as emissivity and reflected apparent temperature, the door is wide open for mistakes. The cameras are simpler to use, the IR physics of the targets hasn't changed. Skilled thermographers using the "high end" cameras recognize the importance of good training and actively support it. IR training has become a very important part of the infrared community. Unfortunately, the message is often not received by the "low end" users even with online training courses, newsletters and other media.

A challenge for Thermosense is to continue to increase the technical expertise of the "gurus" of the infrared community, while working to further the standards for training and certification of all users of infrared thermography. Unskilled users risk millions of dollars of company assets as well as life and limb of themselves and co-workers. After 40 years, Thermosense faces the same type of challenges that gave it birth. They have different faces, but Ignorance is still their middle name. *Nil magnum nisi educatio*.

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