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MEMORANDUM

To: J.M. Stone, 773-41A

From: E.A. Clark, 773-A

SURVEY OF THERMAL IMAGING TECHNOLOGY AND APPLICATIONS AT THE SAVANNAH RIVER SITE (U)

Derivative Classifier: J.P. Howell

Summary

This memorandum is an introduction to thermal imaging systems and their use. Emission of infrared radiation from ideal and real materials is described, as are methods of detection in modern thermal imaging systems. Typical specifications and features of commercially available thermal imaging systems are described, and uses of thermal imaging are discussed. At the Savannah River Site (SRS), thermal imaging has been used extensively to measure the temperature of surface water that carries heat from the reactors to the Savannah River. Other uses at SRS have been surveying roof insulation and moisture, evaluating insulation of prototype glass melters at the TNX facility, and locating leaks in the Concentrate Transfer System.

Future recommended programs include evaluating thermal imaging for general monitoring of plant facilities, especially electrical conduits, processes occurring at elevated temperature, and radioactive storage areas that generate significant amounts of waste heat. Research on the resistance weld techniques used in tritium reservoir handling (pinch welding and reclamation welding) may profit from high speed thermal image monitoring of heat generated during welding, and other Process Development activities may also benefit from high-speed thermal image monitoring.

Introduction

All matter emits radiation characteristic of it's temperature. For temperatures less than about 700°C., this radiation has a wavelength less than that the human eye can detect, and is termed infrared radiation. Since the wavelength of the emitted radiation is determined by the temperature of the emitting matter, infrared radiation is also called thermal radiation. Thermal imaging and infrared imaging refer to the detection of thermal radiation and it's analysis and presentation as an image. The brightness of the image in thermal imaging systems is related to the temperature of the surfaces of the bodies in the field of view of the image. Modern thermal imaging systems have been developed which combine ease of use, accurate temperature measurement capabilities, and rapid image formation. In addition, the recent development of digital image analysis technology[1] has greatly enhanced the capabilities of thermal imaging systems.

Since all matter emits thermal energy at temperatures greater than absolute zero, the application of thermal imaging systems is in principle quite broad. Thermal imaging has been used to: study road traffic patterns[2], inspect jet engine turbine blades[3], monitor resistance spot welding[4], evaluate substation transformers[5], and measure heat losses from buildings[6]. Using digital image analysis, a thermal image can be subtracted from a reference image of the same area to reveal the development of local hot spots before failure occurs[7]. The detection of electrical system weak points, discovery of inadequate insulation of pipes and mounting fixtures, observation of "hot spots" due to carbon build up in diesel motors, and assuring proper emergency spray flow rates have been accomplished in nuclear power reactors[8]. Thermal imaging was used to study the propagation of flames in controlled studies of ignition of liquified natural gas[9].

Infrared Emission and Detection

The total radiated power R from a ideal black body, or the radiation emitted from a small hole in an enclosed cavity, at a temperature T (of the inside of the cavity) is given by Stefan's law:

$$(1) \qquad R = \sigma * T^4$$

where $\sigma = 5.67$ Watt/m^2/°K^4 is the Stefan-Boltzmann constant. The spectral radiated power R_λ at wavelength λ is defined from:

(2) $$R = \int_0^\infty R_\lambda \, d\lambda.$$

The form of the Planck Radiation Law[10]:

(3) $$R_\lambda = c_1/\lambda^5 * 1/(\exp(c_2/\lambda * T)-1)$$

explicitly describes the dependence of the spectral radiated power on λ and T and constants $c_1 = 3.74*10^{-16}$ Watt*m^2 and $c_2 = 0.0144$ °K*m. This equation give the power per unit area of radiation emitted at each wavelength from the hole of a black body cavity. The temperature in Eq. 3 is that of the inside of the cavity. The spectral power emitted according to Eq. 3 is plotted versus wavelength in Fig. 1 for several temperatures, which also shows shaded regions representing infrared wavelength bands readily transmitted through air. Because of this transmission characteristic, thermal imaging detectors are designed to detect either the 3-5 µm band or the 8-12 µm band[11]. The choice of band for a given application is influenced by the range of temperatures of bodies to be monitored: the 8-12 µm band is appropriate for ambient temperature, and the 3-5 µm band is preferable for higher temperature studies, because each band corresponds to the maximum power radiated for a given temperature in Fig. 1.

Real materials are not shaped like the idealized black body discussed above, and often do not emit as much infrared radiation as predicted by Eq. 1. The total emissivity ε and spectral emissivity ε_λ are defined[10] as:

(4a) $$\varepsilon = R_{actual}/R_{black\ body}$$

(4b) $$\varepsilon_\lambda = R_{\lambda,\ actual}/R_{\lambda,\ black\ body},$$

the ratios of the actual emitted power of a material at a given temperature to that of a black body at the same temperature (ε and ε_λ must be between 0 and 1). The total emissivity of conductive metals is generally much lower than insulators, and for a given material can vary significantly with surface finish, shape, and degree of oxidation, as well as temperature; the spectral emissivity can also vary with wavelength[12].

The variability of emissivity causes uncertainty in assigning a value of temperature to a given detected intensity in thermal images. Absolute temperatures can be calculated if the emissivity of materials under conditions in the thermal images are known. (If a suitable black tape or paint is put on bodies in the image, the emissivity of the tape is known (and is close to 1) and the temperature of each body can thus be calibrated.) Increased accuracy of absolute temperature measurements is possible by recording thermal images in both wavelength bands; this can be done either simultaneously[13] or in succession[14] (if the a process being investigated is unchanged in the time it takes to record the two thermal images).

Modern Thermal Imaging Systems

Many thermal imaging systems are available having a variety of features[15]. Most use linear array detectors based on mercury-cadmium-telluride (Hg-Cd-Te or MCT); some use indium antimonide (InSb) for the 3-5 μm band. Use of both of these detectors requires cooling and this is done by either liquid nitrogen or thermo-electric cooling systems (at greater expense but with greater convenience). At least one system is available with simultaneous detection of both the 3-5 μm and the 8-12 μm bands. By choice of detection band and use of suitable filters, images having temperatures between -20° and 1500° Celsius are measurable. Filters are available that, for example, suppress the image of flames when objects inside or beyond the flame is monitored, and suppress the radiation from sunlight that may interfere with temperature measurement of sunlit surfaces.

Thermal image spatial resolution is normally about 200 vertical lines by 256 horizontal positions, with the actual area in the field of view (and thus smallest resolvable area) determined by the lens chosen. Because of the wide choice of infrared lenses available, areas from as small as 1.6 mm by 1.6 mm to as large as an entire plant can be imaged. Reference infrared sources inside the camera allow automatic calibration after each scan, and this greatly reduces drift of system calibration during use.

A typical scan speed is 25 frames per second. This corresponds to a time resolution of about 40 milliseconds for each point in an entire image. Optional scan modes are available that sense the temperature along a horizontal line at a rate of about 2500 lines per second, which corresponds to a time resolution of 40 microseconds. The normal scan rate is limited by the mechanical device that enables vertical scanning of the horizontal array of detectors; when this is turned off in the line scan mode, the scan rate is limited only by the electrical response of the detector and control electronics.

Thermal imaging systems (including camera and electronic controller with image monitor and numeric information display) are made for use in the field; they are compact, portable (can be put on a one-man moveable cart) and rugged (at least according to the manufacturer's literature![15]). Some systems have the capability of temperature readout at operator selected points in the image, and alarm values for each of the selected points can be set in the system that cause warning messages to be displayed. The fullest use of thermal imaging systems comes after digitizing the image and analysis using an image analysis system, and so a desireable system would have a portable camera and controller with modest analytical capabilities for field use and a video cassette recorder; an image analysis system in the laboratory would allow subsequent detailed analysis of the recorded thermal images.

Many forms of digital image analysis[1] are applicable to thermal images. Thermal image analysis techniques are specialized because of the unique interpretation of the image intensity at each point as temperature. Commercial thermal image analysis systems can calculate object temperatures if emissivities of the objects are known, or can estimate temperature by calculation in the absence of emissivity data. Image subtraction promises to be an extremely important tool, when thermal images are taken over time and compared to images made under "normal" conditions to detect changes in operating conditions. (This a common way of detecting "hot spots" or electrical flaws[7], discussed above.) Additional display capabilities that aid in thermal image interpretation include: presentation of image isotherms in pseudo-color, line display of temperature, calculation and display of thermal gradients along a user specified line, calculation and display of maximum, minimum, mean and deviation of temperatures in a user-defined area on the image, and simultaneous display of multiple (up to four) separate images which facilitates comparison between images. Of course, features of general image analysis[1] including image enhancement (noise reduction and contrast enhancement) and quantitative metallography (analysis of area fractions and area sizes and counting of features) are fully applicable to digitized thermal images.

Previous Thermal Imaging Applications at SRS

Thermal imaging technology has found various applications at the Savannah River Site (SRS). Examples include[16]: a site-wide survey of roof insulation and moisture (which resulted in a major program of re-roofing), evaluation of insulation of experimental glass melters at the TNX facility, and a determination of which of several tritium reservoirs in a common secondary container leaked (by observing that one reservoir was cooler than the others; tritium containing reservoirs are warmed by the decay heat of tritium). Thermal imaging was used to locate the position of leaking in the Concentrate Transfer System, in which radioactive waste is transferred through an inner pipe that is in turn surrounded by an outer pipe. By flowing heated water through the inner pipe and thermally imaging the outer pipe, the location of leaks in the inner pipe were detected that could not otherwise using more conventional means of non-destructive evaluation[8,16].

An extensive program of studies of temperature distribution along thermal outfall plumes of the production reactors into the natural drainage system (the Pen Branch and Four Mile Creek deltas that lead from the heat exchangers to the Savannah River) has been done[17]. A specialized thermal imaging/remote sensing system was flown over the area on several occasions over four years, recording thermal intensity in the 8-14 μm band, with a ground resolution of about 5.6 meter by 5.6 meter. The measured temperatures were used to construct and confirm mathematical models of the temperature distribution along the creeks. This method of measuring the temperature distribution was much cheaper and more detailed than obtaining the same information by measuring temperatures on the ground.

Suggestions for Future Uses of Thermal Imaging at SRS

Thermal imaging should be evaluated as an method of monitoring many critical plant facilities. The ability of digitized thermal images to be recorded and the image subtraction capability discussed above make short- and long-term monitoring very attractive for increased safety, quality, and facility efficiency. The decay heat from radioactive materials could allow monitoring of radioactive waste storage facilities in a unique way. This could serve as an assay of the amount of radioactive material as well as a way of detecting leaks in the container of the material. Monitoring of buildings, electrical systems and mechanical devices has already been shown to be effective and useful in both nuclear and non-nuclear facilities[5,6,7,8].

It may be possible to monitor pinch welding and reclamation welding (both solid-state resistance bond techniques) using thermal imaging. The mechanical constraints and weld electrodes used in pinch welding leave only a small observable area on the stem; detailed thermal information may therefore be difficult to obtain for this process. Stem misalignment in reclamation welding can cause local heating and an in turn a bond of uneven quality. Observation of temperature transients using thermal imaging during reclamation welding may allow assessment of the effects of stem misalignment, especially comparing the various differing reservoir types. Thermal imaging studies of both pinch and reclamation welding would require rapid (>600 Hz) acquisition of data, and either the line scan feature discussed above or a special system may be necessary for these studies. Processes under study in the Weapons Technology group of Hydrogen Technology may benefit from similar studies of rapid thermal transients during process activities.

Equipment Engineering Section has a thermal imaging system that can be used for scoping studies to find possible uses for thermal imaging at SRS[16]. Contacts with custodians of this equipment should be contacted and plans made to schedule it's use. Purchase of options or additions to this equipment may be required. Purchase of a new system is not recommended until it is determined that an application exists for which this system is inadequate. Some applications may require using digital image analysis systems being purchased in SRL.

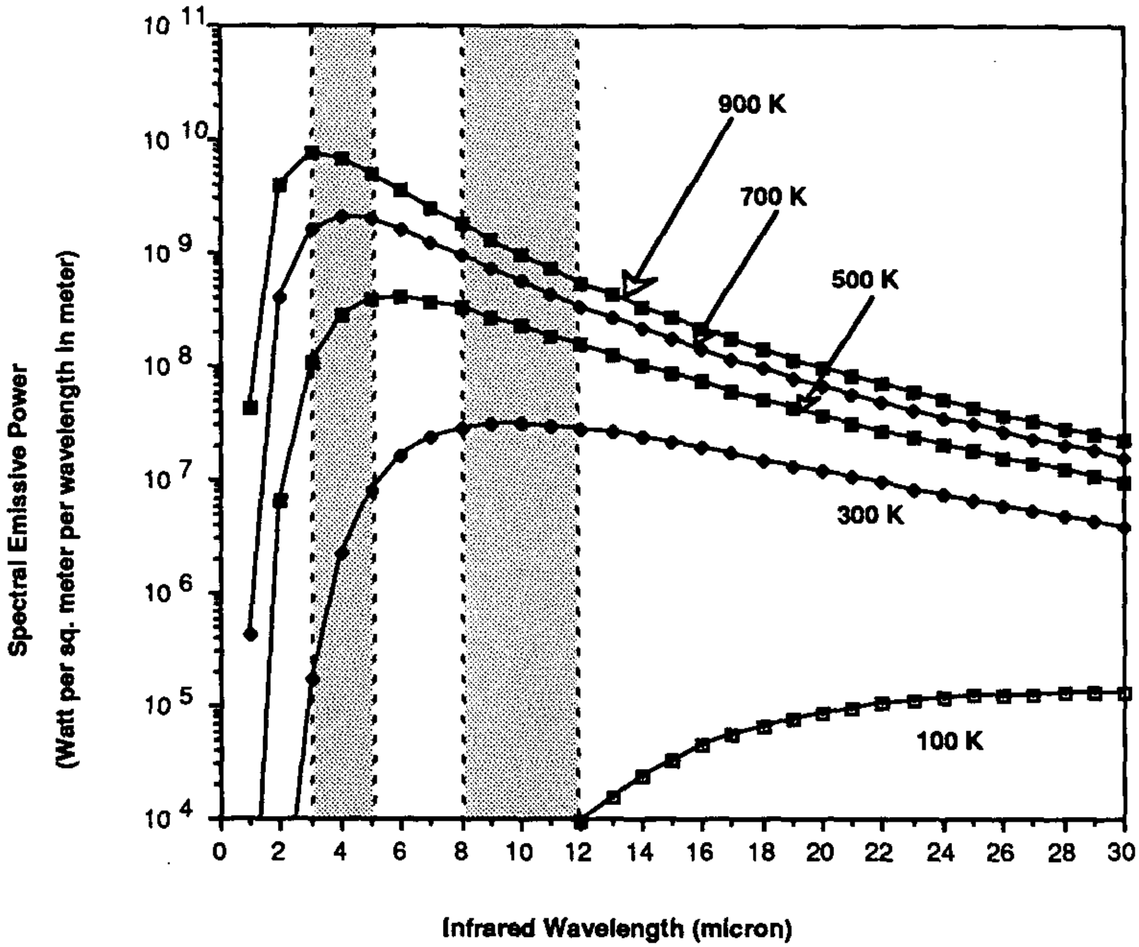

Figure 1. Spectral Emissive Power R_λ versus wavelength λ according to the Planck law (Eq. 3 in text). Shaded regions are infrared wavelengths transmitted through air. Note maximum in 300°K curve in 8-12 μm band, and maximum in 700°K in 3-5 μm band.

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