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A Survey of Infrared Technology for Special Nuclear Materials Control and Accounting

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A SURVEY OF INFRARED TECHNOLOGY FOR SPECIAL NUCLEAR MATERIALS CONTROL AND ACCOUNTING

by

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ABSTRACT

This report reviews some aspects of current infrared measurement technology and suggests two applications in which it may be used in nuclear safeguards. These applications include both materials control and materials accounting. In each case, the measurements rely on passive detection of infrared radiation generated from the heat produced by the radioactive decay of plutonium. Both imaging and non-imaging techniques are discussed.

I. INTRODUCTION

Modern electro-optics has made possible the extension of human vision to regions outside the visible portion of the electromagnetic spectrum. This extension has allowed access to information about the source of the radiation and the intermediate medium of transmission that would not previously have been available. In addition, new sources of radiation have allowed active probing of targets to obtain additional information. A region of the spectrum of particular current interest is infrared (ir) radiation. Much of the new ir technology has been driven by the needs of the military and the communications industry. Infrared systems are used by the military to provide night vision and to detect warm objects such as missile and aircraft exhausts, vehicle engines, or even people. In communications, fiber-optic lines are increasingly being used to replace conventional metallic lines. Glass fibers currently in use transmit ir optimally.

In this report we examine possible uses of ir to help control and account for nuclear materials. This application is attractive because the heat released by the radioactive decay of these materials results in the emission of ir. Because nuclear materials are their own source of ir, we limit the discussion here to passive techniques, that is, those that do not use a source of ir other than the nuclear material. We first summarize some aspects of the physics of the ir including the characteristics of the ir signal generated by nuclear materials, as well as the transmission of ir. This is followed by a presentation of the technology of ir measurement. Topics included are the characteristics and operation of ir detectors, the characteristics and operation of ir imaging systems, and the use of data processing systems to enhance the information yields from ir systems. Finally, we present some research opportunities that take advantage of ir to improve nuclear materials control and accounting.

II. INFRARED PHYSICS

In this section we discuss the physics of ir as it applies to possible use in materials control and accounting (MC&A). This will include the mechanism of emitting ir, the characteristics of ir, and the transmission of ir between the source and the detection system.

A. Emission of Infrared Radiation

All objects emit electromagnetic radiation. For objects near room temperature, much of the emission takes place in the ir region of the electromagnetic spectrum. This is the wavelength band between 0.8 and 200 µm. The actual amount of energy and the wavelength distribution of emission are a function of the temperature of the object. The total energy output per unit area is given by the Stefan-Boltzman Law

$$R = \epsilon \sigma T^4 \tag{1}$$

where R is the radiancy (energy per unit area), T is the absolute temperature, and σ is the Stefan-Boltzman constant, which has a value of 5.67×10^{-8} for R in W/m^2 and T in degrees Kelvin. The total emittance is ϵ—a unitless number between zero and one. The intensity of the emission as a function of wavelength is given by the Planck equation

$$R_\lambda = \frac{C_1}{\lambda^5} \frac{\epsilon_\lambda}{e^{C_2/\lambda T} - 1} \tag{2}$$

where R_λ is the spectral radiant emittance in watts/cm^2 µm, λ is the wavelength in µm, ϵ_λ is the spectral emittance at that wavelength, and T is the temperature in degrees Kelvin. The constants c_1 and c_2 have the values 3.74×10^{-12} W cm^2 and 1.4388 cm K, respectively.

The wavelength of maximum emission is given by the Wien formula

$$\lambda_{max} = \frac{2897\epsilon}{T} \tag{3}$$

where λ_{max}, the wavelength, is in µm, and T is in degrees Kelvin.

The emittance term in the last two equations is a measure of the amount by which an object deviates from the properties of a blackbody. A blackbody is a perfect emitter and absorber of radiant energy. For an opaque object, emittance and reflectance are defined such that

$$\epsilon + r = 1 \tag{4}$$

This means that a very reflective object such as a polished metal surface has a very low emissivity. Emittance is a property of the surface of an object, thus it can be changed by modifying the surface of a bulk object by applying a coating or changing the surface roughness. Emittance is also a weak function of wavelength. The emission in a given wavelength region is called the spectral emittance. Table I gives the total emittance for a number of different surfaces.

TABLE I

TOTAL EMITTANCE OF COMMON SURFACES[1]

Surface	Emissivity
Polished aluminum	0.04-0.06
Heavily oxidized aluminum	0.2-0.33
Stainless steel	0.25
Water	0.92-0.96
Paper	0.92
Oil paints, all colors	0.92-0.96
Candle soot	0.952

There are several consequences of Eqs. (1) and (2) for ir temperature measurement. First, because of Eq. (1), a very small change in temperature causes a very large change in emitted energy. Second, from Eq. (2), an increase in temperature causes a decrease in the wavelength of maximum emission. However, there is an increase in the emission at any wavelength. All of these features are seen in Fig. 1, which shows the energy emitted per square centimeter of surface area in each µm of the spectrum.

B. Transmission of Infrared

Infrared is absorbed by the vibrational and electronic modes of some molecules and crystalline solids. This absorption is limited to certain wavelength bands so that a material may be relatively transparent in one part of the spectrum and opaque in another. This fact may be used to optimize the transmission of ir through media and to produce filters to exclude certain parts of the electro-magnetic spectrum.

1. Atmospheric Transmission of Infrared. In almost any application of ir technology to safeguards, the emitted radiation will have to be transmitted through the atmosphere for some distance. This makes it critical to understand the ir absorption characteristics of the atmosphere. Air is composed of a mixture of gases. The most important of these for these purposes are oxygen, nitrogen, carbon dioxide, and water vapor. At the abundance and pressure found under normal ambient conditions, the major contributors to the absorption of ir are carbon dioxide and water vapor. However, there are several transmission "windows" at about 1 µm, 2-2.5 µm, 3.5-4.2 µm, and 8-14 µm. Notice that the wavelength of maximum emission of an object near room temperature falls conveniently in this last window.

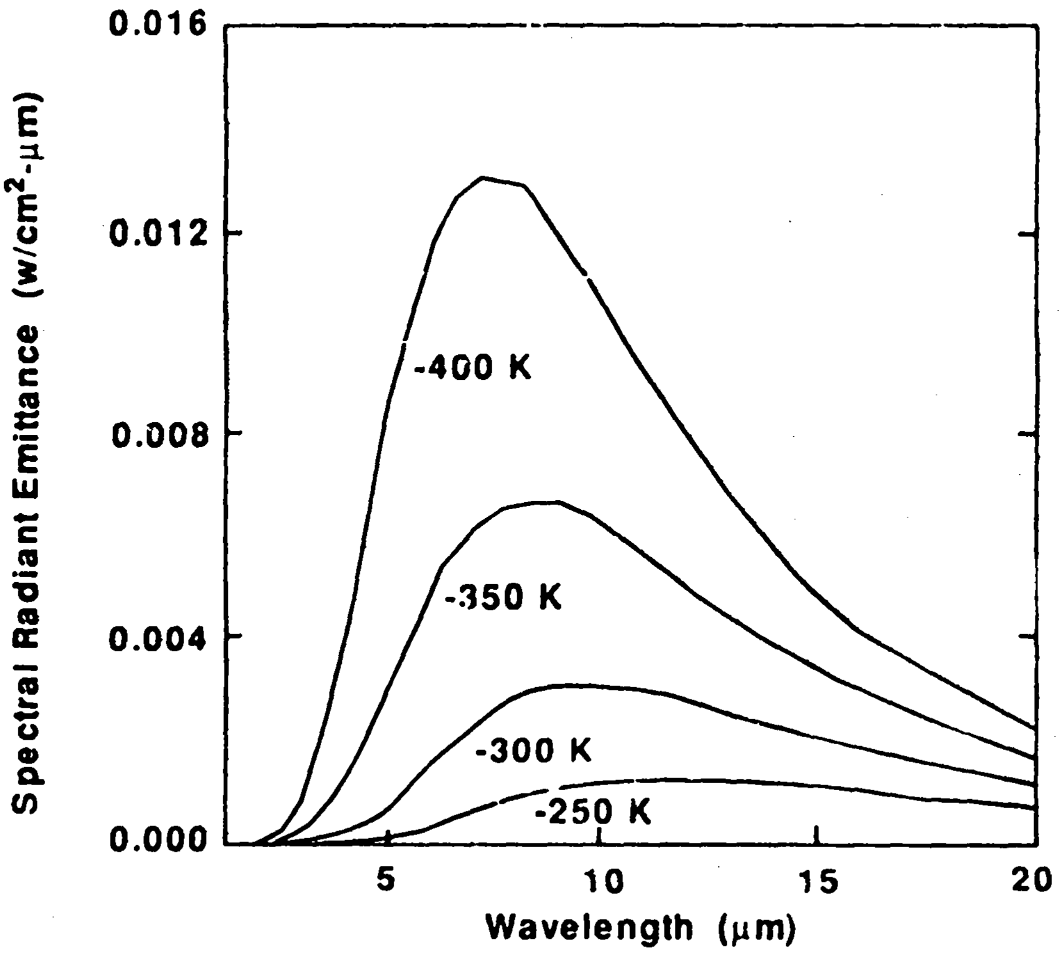

Fig. 1. Distribution of radiant emittance with wavelength for a blackbody at various temperatures.

2. Transmission of Infrared in Crystalline Solids. The electronic structure of crystalline solids is different from the electronic structure of a molecule in that the valence orbitals of the individual atoms fuse into bands that cover the entire crystal. Conduction results when these bands are not filled. The charge carriers can be viewed either as individual electrons or as holes in an electron sea. The electrons are negatively charged carriers and the holes are positively charged carriers. A material with totally filled and totally empty bands is an insulator. A material with a partially filled band is a conductor. A material with a filled lower band, the valence band, separated by a small gap from an empty higher band, the conduction band, is called a semiconductor. This is shown schematically in Fig. 2.

The mechanism of ir absorption in crystalline solids involves promotion of electrons (or holes) into higher energy bands of the material. This process is of importance in the production of ir detectors and will be discussed further in the following section on detectors. Only radiation with enough energy to promote the electrons (or holes) will be absorbed. Therefore, solids have well-defined regions of transparency that allow materials to act as windows and filters. A common example is silicon. Silicon does not transmit at wavelengths below 1.2 μm, but is transparent at longer wavelengths. Therefore, silicon is a good choice for a window material that excludes visible light but allows the transmission of ir.

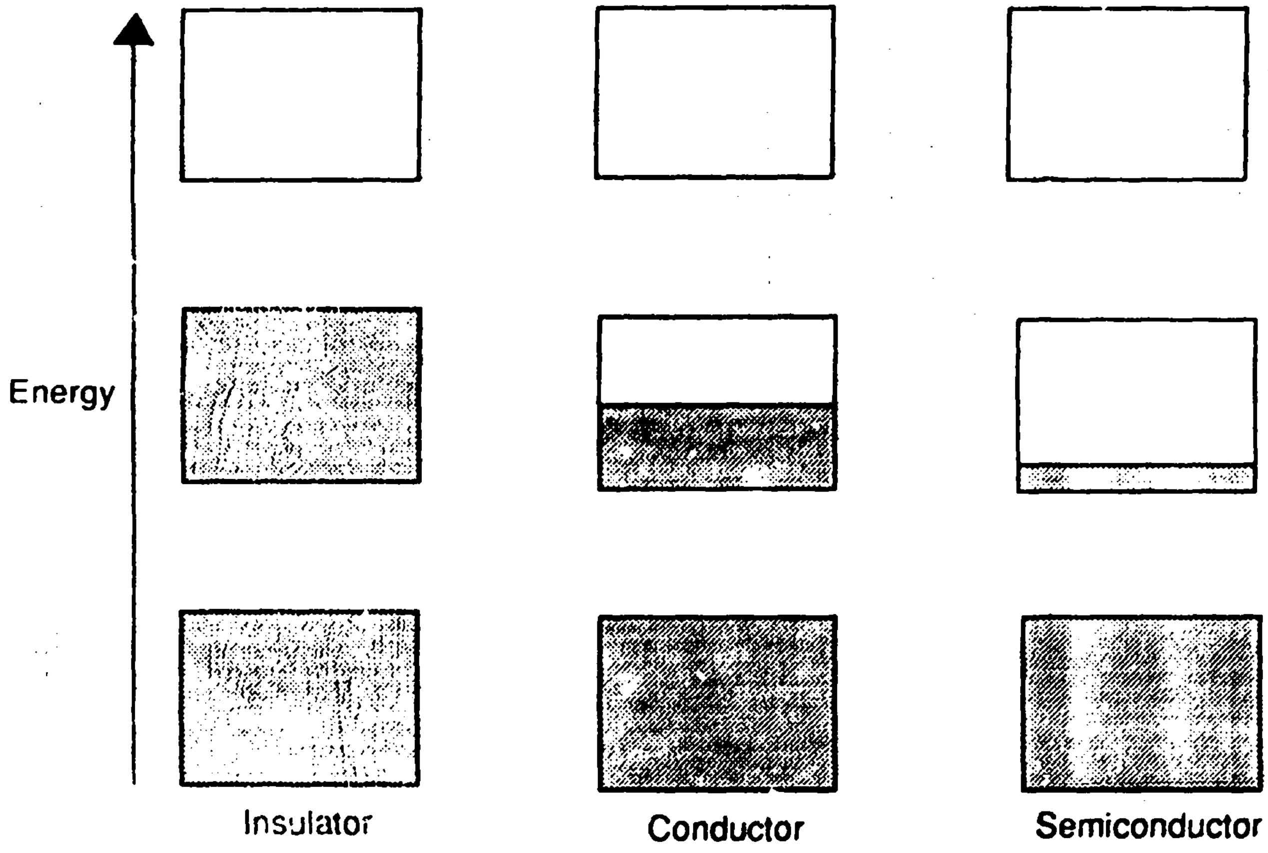

Fig. 2. Schematic representation of the electronic structure of an insulator, a conductor, and a semiconductor.

III. INFRARED TECHNOLOGY

A. Infrared Detectors

Infrared detectors are of two basic types, thermal detectors and quantum or photon detectors. Thermal detectors work by measuring a change in temperature caused by the absorption of the ir. These were the first type of ir detector developed. The output of quantum detectors results from the direct interaction of the detector electrons with a quantum of light, a photon. A common quantum detector is an inorganic semiconductor with appropriate metallic leads attached. (Another type of photon detector, a red-sensitive photomultiplier tube, can be used in the near-infrared. However, these tubes have relatively little utility for measuring emissions from near-room-temperature objects so they will not be considered further.) As described above, when a photon impinges on a semiconductor, the photon can change the electronic structure of the solid. Semiconductors can change from an insulator to a conductor. The manipulation and measurement of this change is the basis of all solid state ir detectors.

1. Thermal Infrared Detectors. As stated above, thermal detectors work by measuring a temperature change induced by the absorption of ir radiation. The actual devices include thermocouples and thermopiles, thermistors, pneumatic detectors, and pyroelectric detectors. A thermocouple or thermopile (a stack of several thermocouples) senses temperature as a change in the potential across a bimetallic junction. A thermistor system is based on a temperature sensitive resistor. A pneumatic detector, also called a Goulay cell, works by measuring the pressure change in a gas-filled bulb when it is heated by the ir radiation. A pyroelectric detector consists of a ferroelectric crystal such as deuterated triglycine sulfate or $LiTaO_3$, which has a permanent internal dipole moment. In an actual device, these dipoles exist as a number of domains. When a dc field is applied, most, but not all, of the domains line up with the field. The number of domains that do not line up changes with the temperature. The imbalance will induce a transient current proportional to the temperature. A chopped ir beam will then produce an ac signal proportional to the temperature.

Thermal detectors are used most in the mid- and far-infrared. Their greatest utility is that they can produce signals that are relatively independent of wavelength. This makes them very useful as detectors for dispersive devices such as spectrophotometers.

2. **Quantum Detectors.** Materials for quantum detectors are of two types, intrinsic and extrinsic. Intrinsic materials are naturally photosensitive at the wavelengths of interest. Extrinsic materials require that an impurity be introduced to create localized energy levels between the valence and conduction bands so that absorption will take place at longer wavelengths (lower energies) than would normally be the case. Although these materials could be used directly as photodetectors by measuring the change in conductivity, the usual practice today is to fabricate photodiodes or phototransistors.

Photodiodes can be fashioned to create either junction, p-i-n, or avalanche photodiodes. All three devices are based on the production of areas of the crystal that have either excess electrons (n region) or excess holes (p region). These areas are produced by "doping" areas of a crystal with atoms with either fewer or more valence electrons than the native semiconductor.

In the junction photodiode, the n and p regions touch to form a p-n junction. A potential gradient exists at the junction. When a photon is absorbed near this region, electron-hole pairs are formed that can migrate in the gradient. With no external fields applied, the motion of the charges will generate a voltage across the device that causes a current in the external circuit. This is called the photovoltaic mode. If the potential gradient is resisted with a reverse-bias field, the result of the photon absorption is an increase in conduction and therefore current in an external circuit. This is called the photoconductive mode and results in a longer linear response region and a faster response time at the cost of more noise.

The p-i-n photodiode is similar to the junction photodiode except that there is a layer of the intrinsic (native) semiconductor between the p and n regions. This i region results in a greater photon absorption. Also, because of the greater internal resistance, there is a larger voltage drop across the device leading to faster carrier movement. This decreases the response time.

An avalanche photodiode is a junction photodiode with a very high reverse bias. The resulting acceleration of the charge carriers causes collisions that create more charge carriers, much as in a photomultiplier. This amplifies the signal at the cost of increased noise.

A phototransistor is a device similar to a conventional transistor, but with light playing the role of the gate that regulates current flow. Phototransistors produce more current than a photodiode but are slower. Phototransistors have not been as widely used as photodiodes.

The response of quantum detectors as a function of wavelength is determined by the optical properties of the materials. Table II shows the materials of choice for the atmospheric absorption windows.

TABLE II
QUANTUM INFRARED DETECTOR MATERIALS OF CHOICE

Atmospheric Window	Material
1 µm	Si
2-2.5 µm	PbS
3.5-4.2 µm	PtSi
8-14 µm	HgCdTe

The ultimate limit on the sensitivity of quantum detectors is thermal noise. This is caused by the creation of carriers by thermal promotion of electrons into the conduction band. This is a particular problem with materials that have a low-energy gap and are therefore sensitive at long wavelengths. The thermal noise can be reduced considerably by cooling the detector. This can be done using a specially constructed dewar containing liquid nitrogen or helium or with various mechanical and thermoelectric refrigeration systems. The exact amount of cooling necessary depends on the detector material.

3. Detector Figures of Merit. Numerous parameters are used in comparing detector performance. Among the most important are the responsivity (R), the rise time, the noise equivalent power (NEP), the detectivity (D), and the specific detectivity (D^*). These parameters are also usually a function of the wavelength of the light and the modulation frequency if the light is modulated, such as, by a chopper.

The quantity R is the basic output of the detector for a given power input. It may be voltage or current per watt of radiation input.

The rise time is the time interval for the output to rise from 10% to 90% of the final response after a step change in input. In some systems the fall time is also important. For some classes of detectors, the fall time and rise time are not equal, and the fall time may have more than one component.

The NEP is the amount of light power incident on the detector that produces a response equal to the root-mean-square noise voltage. For systems that are noise limited (which is usually the case), D is equal to the reciprocal of NEP.

D^* is defined as $D\,(A\,\Delta f)^{1/2}$, where A is the area of the detector and Δf is the bandwidth of the associated electronics.

For quantum detectors an additional figure of merit is the quantum efficiency. This is the number of charge carriers created per photon.

B. Imaging

Instruments that determine temperature by measuring the amount of radiant energy in a given spectral band are known as radiation thermometers and have been widely used for non-contact thermal measurements for over 50 years. These instruments may be manually operated or automated, portable and battery powered, or designed for a fixed installation. A basic radiation thermometer, shown in Fig. 3, uses telescopic optics to focus the incoming radiance on an

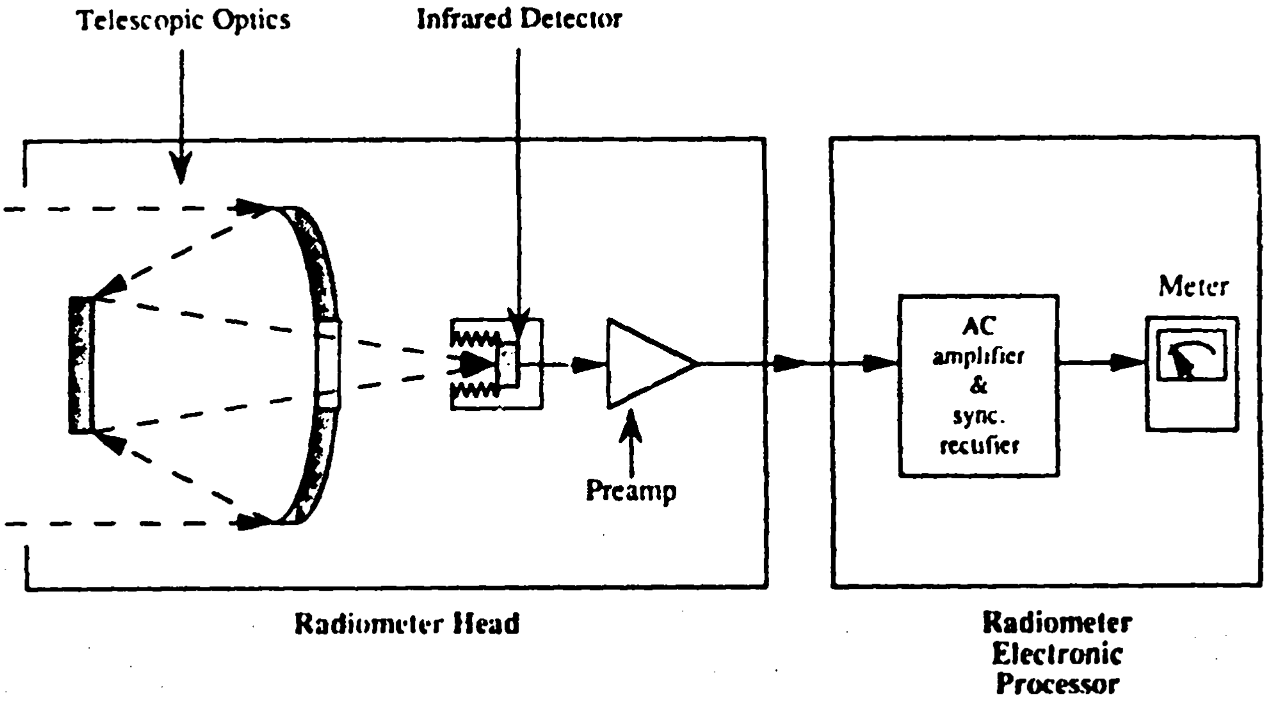

Fig. 3. Basic radiation thermometer.

ir detector. Once digitized, this signal can be amplified or filtered and finally converted to a temperature readout on a meter or a digital display.

Among these radiation thermometers are optical pyrometers, amplitude-sensing radiation thermometers, dual-wavelength radiation thermometers, and specialized fiber-optic radiation thermometers. Optical pyrometers are manually operated instruments using a lamp filament current in conjunction with a red filter to determine the temperature of the target. Battery powered, hand held, and trigger activated, these instruments are primarily used to measure the temperature of substances that have reached luminosity, such as molten steel.

In amplitude-sensing radiation thermometers, the detector electronically converts the incoming radiance into an electronic signal that is then converted to a temperature. Dual wavelength thermometers take measurements at two wavelengths to determine the slope of the radiation curve (as opposed to the magnitude of the radiation) and use the slope to determine the temperature. This technique is useful in conditions where emissivity is a problem, or where atmospheric attenuation exists.

In contrast to radiation thermometers are thermal-imaging radiometers, which generate thermograms—photographic, two-dimensional records of images that map the apparent temperature of a scene onto a medium useful for analysis by humans or machine. As with a radiation thermometer, the type of sensor used by any given thermal radiometer is seldom apparent to the operator. Typically, one or several sensors are used to produce signals that are scanned mechanically across an attached video screen using scan-conversion circuitry (D/A) to create TV-compatible images. These images may then be manipulated using software or hardware image processing techniques, and/or stored in computer memories or peripheral storage devices.

The images produced by thermal-imaging radiometers display heat patterns and produce temperature information by inferring temperature from measured radiant energy. Because all objects radiate energy that is distributed over a band of wavelengths in the electromagnetic spectrum (Fig. 1) and because the energy radiated increases with temperature, it is possible to use the Planck function to determine the spectral distribution of an object at a specific temperature. A consistent relationship between temperature and radiated energy allows a calibrated radiation thermometer to produce accurate non-contact temperature measurements.[2-3]

When coupled with microprocessor-based computer systems, this information can be supplied in real time, allowing rapid assessment of a scene by the operator and/or computerized analysis techniques. While these systems are more costly than other noncontact thermometers, the faster response time and the ability to display exactly what is being imaged, coupled with the ability to process the information as it is acquired have proven them to be valuable tools in both research and industry.[2-4]

C. Data Processing

1. Image Processing and Analysis. Recent advances in computer and microprocessor technologies have increased the usefulness of instruments such as thermal-imaging radiometers. When advanced ir sensors are coupled with video display technology, analog to digital conversion capability, and general-purpose or specialized computer systems, the thermal-imaging radiometer becomes a powerful tool for processing and analyzing ir image data.

Image processing techniques allow the manipulation of digitized image data through the use of software or specialized hardware. Techniques that are frequently used with ir images include image filtering, image averaging, pseudo-coloring of image data, and data compression. Image filters and image averaging techniques are widely used to digitally improve aspects of the captured analog signal. Filters are also used to sharpen, smooth, or improve contrast in images, again improving the quality of the image. For example, small samples of an object's radiation may result in an image containing thermal "noise." This noise appears as snow that is seen on the video monitor when the image is displayed.

Averaging multiple-image samples will also reduce this noise level by the square root of the number of samples averaged, thus improving the overall clarity of the thermal image. Images that lack adequate contrast are frequently processed using histogram equalization; first, the lowest and highest gray scale values for the image are determined, for example, 37 and 190. Each gray scale value is then mapped, or "stretched," to represent the entire gray-scale range from 0 to 255. Such methods process data to achieve a specific transformation that enhances the information content of the original data.

Pseudo-coloring is especially effective on ir images. Thermograms portrayed in black and white effectively delineate spatial variations but do not present precise temperature detail because the human eye is not able to resolve slight gray-scale variations. Selectively coloring the image by mapping color to specific gray-scale ranges clearly delineates even minute differences in temperature. Typically pseudo-coloring schemes will portray hotter regions in shades of red, cooler regions in blue and purple, and the median temperatures in yellow and orange. However, because pseudo-coloring is usually implemented in software, the color mapping can be specialized to bring out any specific thermal characteristic displayed by a thermal image. Further, Centigrade or Fahrenheit temperatures can be mapped to the color scheme, thus displaying an exact temperature (within instrument tolerances) for a given colored region.[5]

a. Image Averaging. An image can be represented as a function $f(x,y)$ where x and y are coordinates on the display. A method of image processing involves changing or transforming the original image $f(x,y)$ into a new image $g(x,y)$; the actual transformation can be represented by T.

$$g(x,y) = T\,f(x,y)$$

A standard method for processing images is determining the neighborhood size. In Fig. 4 the neighborhood size is a 3 by 3 array with the pixel of interest in the middle of the array. The method of image averaging looks at pixel values within a specified neighborhood and modifies the values based on a mask or template (see Fig. 5). This technique is very useful for enhancing images that have a uniform intensity with splotches of isolated widely varying pixel values. By using neighborhood averaging, one smooths over the unwanted splotches.

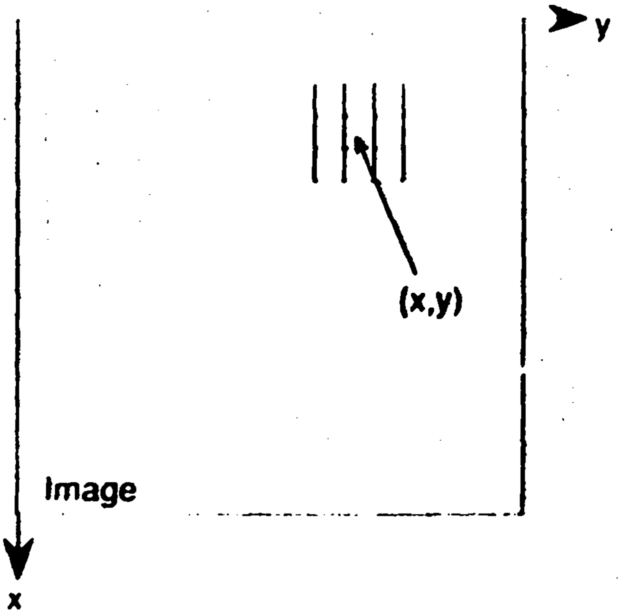

Fig. 4. A 3 × 3 neighborhood around a point (x,y).

-1	-1	-1
-1	8	-1
-1	-1	-1

Fig. 5. A mask for detecting splotches in an image of uniform intensity.

The following equation and Fig. 6 outline the procedure.

$$\begin{aligned} T\,f(x,y) = {} & q_1 f(x-1,y-1) + q_2 f(x-1,y) + q_3 f(x-1,y+1) + q_4 f(x,y-1) \\ & + q_5 f(x,y) + q_6 f(x,y+1) + q_7 f(x+1,y-1) + q_8 f(x+1,y) \\ & + q_9 f(x+1,y+1) \end{aligned}$$

q_1 (x-1,y-1)	q_2 (x-1,y)	q_3 (x-1,y+1)
q_4 (x,y-1)	q_5 (x,y)	q_6 (x,y+1)
q_7 (x+1,y-1)	q_8 (x+1,y)	q_9 (x+1,y+1)

Fig. 6. A mask with the transformation coefficients.

At each pixel position in the image one multiplies the mask value by the actual pixel values of the image. If the sum of the above equation is zero, then the area of the image is of a uniform intensity. If on the other hand, the sum is not zero, then the particular area of the image, based on some threshold value, is a splotch. The area of splotches can be eliminated by changing the pixel values towards the uniform intensity of the other pixels in the region.

b. Histogram Modification. Let the variable x denote the gray levels of the pixels in an image. The original values of the pixels were between 0 and 255 with 0 representing black and 255 representing white. Using a normalization process, the values were scaled down to the range between 0 and 1.

$$0 \leq x \leq 1$$

By defining a transformation function T (see Fig. 7), one is able to change the image at each pixel value x and produce a new pixel value y.

$$y = T(x)$$

By *modifying* the transformation function T, one is able to adjust the image towards either a lighter range where the pixel values are skewed towards zero or towards a darker range where the pixel values are closer to 1.

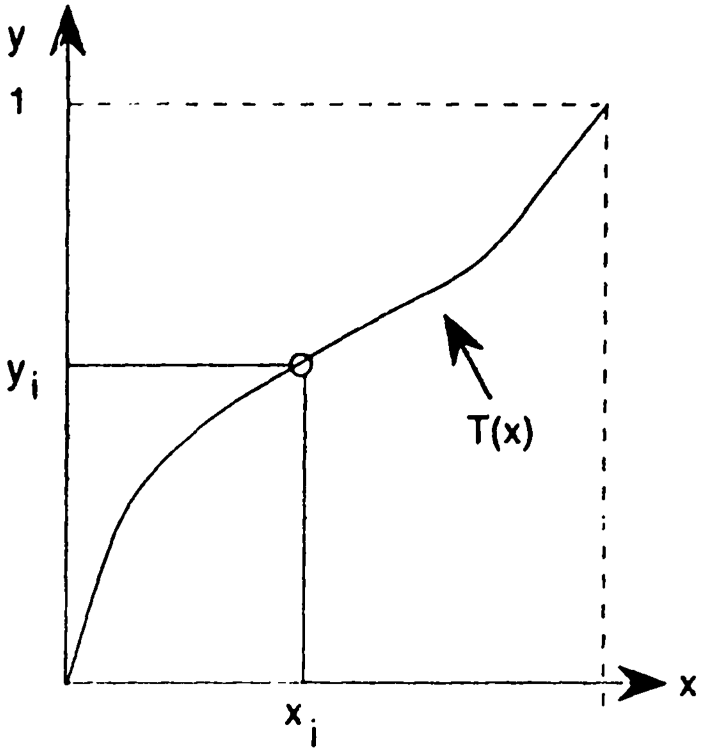

Fig. 7. A gray-level transformation function.

c. Histogram Equalization. Let a 32 by 32, 8-level image have the following distribution.

x_i	Number of Pixels	Probability
$x_0 = 0.00$	10	0.010
$x_1 = 0.14$	15	0.015
$x_2 = 0.28$	350	0.342
$x_3 = 0.43$	410	0.400
$x_4 = 0.57$	200	0.195
$x_5 = 0.71$	24	0.023
$x_6 = 0.86$	10	0.010
$x_7 = 1.00$	5	0.005

A plot of probability versus x_i is called a histogram. Figure 8 depicts a very narrow range of gray values and therefore poor image quality. The method of histogram equalization is a technique used for obtaining a uniform histogram, sometimes called a uniform density or distribution. This standard idea is used often when dealing with probability density functions.

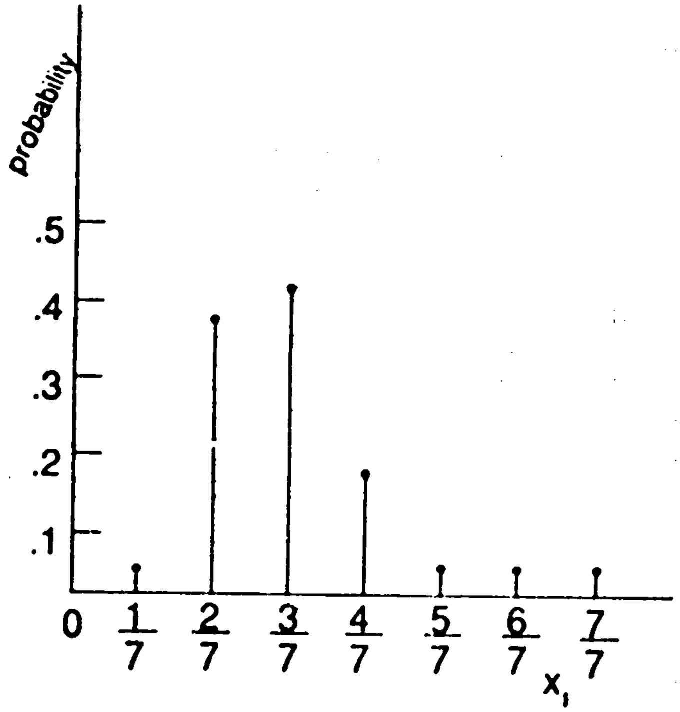

Fig. 8. Histogram for original image.

To improve the quality of the image and increase the dynamic range of the pixels, one uses the following set of equations to come up with the proper uniform histogram:

$$y_i = T(x_i) = \sum_{h=0}^{i} \frac{n_h}{n} = \sum_{h=0}^{i} p_i$$

where $n = 1024$, n_h = number of pixels, and p_i = the probability at each level i.

x_i	y_i	level i
$x_0 = 0.0$	0.010	0
$x_1 = 0.14$	0.025	0
$x_2 = 0.28$	0.367	3
$x_3 = 0.43$	0.767	5
$x_4 = 0.57$	0.962	7
$x_5 = 0.71$	0.985	7
$x_6 = 0.86$	0.995	7
$x_7 = 1.0$	1.00	7

In the above table, the y_i's are calculated and then mapped to the closest x_i level. The number of levels has been reduced to help smooth out the histogram.

level *i*	total pixels	probability
0	25	0.024
3	350	0.342
5	410	0.400
7	239	0.233

As can be seen in Fig. 9, the distribution has been spread out, and therefore the image quality has been enhanced.

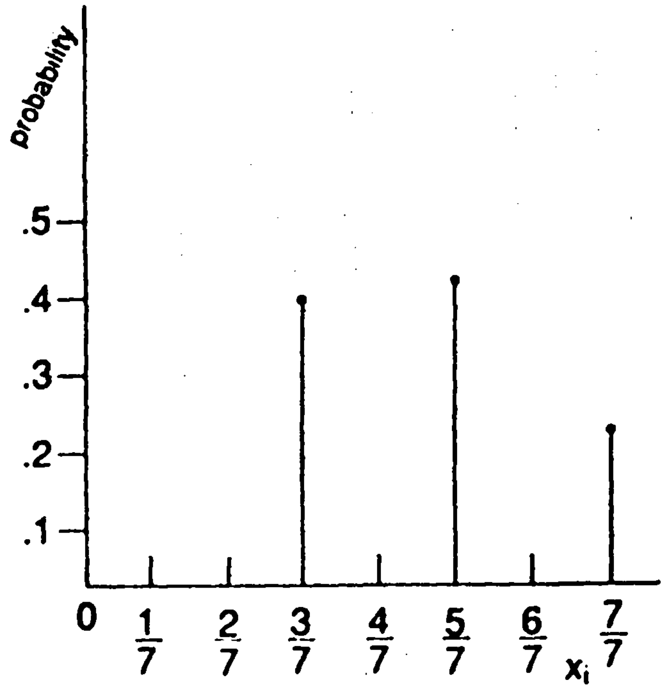

Fig. 9. Histogram for equalized image.

d. Data Compression. One of the newest forms of image compression is based on the ideas of fractal geometry and iterated function systems. An average-size image is around 0.5 megabyte. In the case of satellite imagery in which hundreds of images are broadcast on an hourly basis, problems quickly arise in the area of image transmission and storage.

A set of iterated function systems may be used to represent an image. Each member of the set of functions represents a particular part or section of the image. The difficult part of this method is choosing a function that accurately represents each section of the image. The number of functions needed is based on the complexity of the image. An image with only two objects in it needs only two functions. However, a complex image with many different facets needs many different iterated functions to represent all the details. If one can successfully map or transform an image to a set of equations, then a reduction from 0.5 megabyte to 1 kilobyte can be achieved. This area of research is fascinating but nonetheless challenging.

2. **Signal Conditioning.** Signals generated by a detector are often dominated by noise. The sources of this noise include stray optical signals from unintended ir sources and noise generated by the electrical components, including the detector. The sensitivity of a detection system is not limited by the signal level because it is always possible to provide amplification. Rather the ultimate limit is provided by the signal-to-noise ratio (S/N). In optical systems, several very powerful signal conditioning techniques can be applied. These include signal averaging, filtering, and synchronous detection.

Signal averaging is based on the observation that noise is generally random about the actual signal. The mathematical mean of this noise is zero. Therefore, it is possible to accumulate the signal over some period of time and average out the noise. This averaging can be done either in hardware or software. The price paid for signal averaging is a reduction in response time.

Filtering involves the selective removal of certain frequencies in the signal. This generally involves eliminating frequencies above and/or below the frequency of interest in the belief that there is no significant information in these ranges. This type of filtering is often implemented in hardware. However, sophisticated algorithms are available to filter digital data. With dedicated, high-speed computers, digital filtering can be done in essentially real time. A particularly intriguing class of digital filters is Kalman filters. This is a type of recursive filter that learns to adapt to the data.

Synchronous detection is an extension of the filter concept. The input signal to the detector is modulated at a known frequency. A notch filter set at that frequency is used to remove all unwanted portions of the signal. The consequent increase in S/N allows tremendous amplification. In optical systems the modulation of the input signal is usually accomplished with a mechanical chopper or an acoustic-optic modulator. The synchronous detection is then accomplished with a lock-in amplifier.[6]

3. **System Control.** The introduction of a computer into a measurement system not only facilitates data collection, storage, and analysis but also allows the possibility of using the computer to control the instrument. This can be carried out at the relatively simple level of moving through a pre-programmed set of instructions or at a more sophisticated level in which the instrument adapts itself to changes in environmental and data parameters. In an ir system, this could include periodic recalibration, monitoring detector temperatures, and responding to variations in ambient temperatures. Implementation of this type of intelligence can be through an add-on computer or an embedded microprocessor system. The former has more flexibility while the latter is cheaper and smaller.

IV. APPLICATIONS

A. Imaging

As humans, we rely on our abilities to absorb and assimilate the visual information presented to us in our everyday life; today, no emerging technology has more vital applications in aerospace, defense, industry, and even nuclear safeguards than the emulation of our own vision systems through the integration of artificial sensors, computers, and video displays.

Throughout industry and defense, image processing applications include defect analysis, remote sensing, tracking and warning systems, simulation, digital mapping for guidance systems, and motion detection. Infrared imaging applications have long included industrial and residential energy consumption surveys; structural moisture analysis; inspection of mechanical systems in refineries, generator cores, and steel mills; and industrial preventative maintenance on machinery and electrical systems, to name a few. In the defense arena, applications include night vision systems designed to provide real-time, three-dimensional topographical mapping for airborne platforms; night tracking and target guidance systems; and military change and motion detection systems.[7]

In the nuclear safeguards arena, ir imaging would appear to offer additional signatures that could be used in materials control applications. The internal heat generated by the decay of plutonium provides a signature that an adversary would have to duplicate in addition to the normal video image. This signature consists of the overall increase in temperature of an object holding plutonium. In addition, any patterns in the temperature field could be used as an identifier for a particular object. With commercially available imaging systems having sensitivities of 0.1° or less, such measurements appear to be well within the range of possibility.

B. Infrared Thermal Analysis

Considerable amounts of thermal energy are released during the radioactive decay of some materials, principally the isotopes of plutonium. Table III shows the thermal output of the most common isotopes of plutonium. The heat is generated from the kinetic energy of the alpha and beta particles emitted by the decaying plutonium. If the isotopic composition of a plutonium-containing sample is known, it is then possible to determine the amount of plutonium in a sample by measuring the heat generation. The measurement of heat (calorimetry) offers a number of advantages. Among these are the high precision and accuracy associated with calorimetric measurements, the matrix-independent nature of the measurement, and the applicability to any plutonium-bearing material.[8]

TABLE III

SPECIFIC POWERS OF PLUTONIUM AND AMERICIUM[9]

Isotope	Specific Power (W/g)
^{238}Pu	0.56757
^{239}Pu	0.0019288
^{240}Pu	0.0070824
^{241}Pu	0.003412
^{242}Pu	0.00011594
^{241}Am	0.11423

The attractiveness of heat measurements to determine plutonium composition has led to the development of two types of calorimeters. The principal calorimeter systems in use today are thermal gradient calorimeters that surround the sample with several layers of material to establish a stable thermal gradient. The final layer is a precisely controlled metal block or water bath. Once the system reaches equilibrium, the temperature difference between the sample and the outer temperature is measured. With this type of system, analysis times are quite long (2-6 hours minimum), but accuracies are 0.2% (Ref. 10).

A more recent development is the use of a pre-heated or air-bath calorimeter. In this system, the sample is brought to equilibrium at a temperature above what the sample would normally attain. The sample is then placed in a chamber containing an electric heater with a thermostat. The chamber temperature is controlled to the pre-equilibrium temperature. Once the system reaches thermal equilibrium, the electrical energy required to keep the system at the thermostatted temperature is measured. The higher the power output of the sample, the less electrical heating necessary to hold the temperature. Accuracies with this system are 2 to 5% with an analysis time (not including pre-heating) of 15 to 30 minutes.[10,11]

Although both of these devices are capable of giving excellent results,[8,10,11] they have shortcomings. The very large thermal mass of the conventional calorimeter requires many hours to come to thermal equilibrium. Analysis times of 8 hours or more are not unusual. The pre-heated calorimeter avoids this by pre-equilibrating the sample to the measurement temperature so that only a few tens of minutes are required in the calorimeter before equilibrium is attained. However, this system has poorer precision and accuracy and the pre-heating step is necessary.

Because of its flexibility, an ir-based system may be able to make more rapid measurements than conventional systems without the need for pre-heating. It may be possible to make an ir measurement of the surface temperature of a container holding plutonium and then relate this temperature through the use of standards to the heat output. A significant advantage of such a system would be the more rapid achievement of thermal equilibrium caused by the minimization of the thermal mass of the system. Essentially the only elements involved in the thermal equilibrium are the container itself and some boundary layer near the surface. Before such a system could be constructed, however, it would be necessary to investigate the required amount of environmental isolation as well as the best way to provide a high-emissivity surface on the container.

V. SUMMARY

The modern safeguards environment places unprecedented requirements on the safeguards system. At a time of difficult funding, facilities are being required to improve their safeguards systems while at the same time meet more stringent environmental, safety, and health regulations. This can only be achieved through the development of innovative technologies that both improve the quality and quantity of safeguards information and lower manpower requirements. On the basis of this survey, we believe that both imaging and non-imaging ir measurement methods have a role to play.

Although ir measurement technology is rapidly expanding, it is also in many ways well understood, mature technology. The fact that radioactive materials, particularly plutonium, generate heat and thus ir suggests that it is a natural way to extend traditional safeguards measurement methods. In this report we have suggested two ways in which ir technology may be used to solve safeguards problems. In each case the safeguards application involves the adaptation of readily available, off-the-shelf technology. This significantly reduces the technological risks associated with the development of these techniques while promising a new signature that can be used for safeguards.

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