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U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

Elements of Thermography for Nondestructive Testing

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NBS technical note

Elements of Thermography for Nondestructive Testing

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PREFACE

Thermography, the process whereby the invisible infrared thermal radiation from an object or a scene is rendered into a visible image, is known mainly for its military surveillance and remote-sensing applications. Nevertheless, thermography has great value also in a variety of non-military applications, and is being exploited in agriculture, geology, environmental control, meteorology, medicine, energy conservation, building, and manufacturing industry. In particular, its importance in industry for plant preventive maintenance, process control, quality control, and nondestructive testing has been recognized with the recent establishment of several independent working groups in thermography by different professional societies such as ASTM, ASNT, and SPIE.

This is intended to be a tutorial paper in thermography, especially as it relates to nondestructive testing, for program managers and scientists who are unfamiliar with thermal imaging systems and techniques, and who also may not have a background in infrared physics and technology. The material offered herein gives a simple, broad, and mainly qualitative overview which should help the reader to adjudicate the feasibility of applying thermography for his specific purpose. Notwithstanding, thermography is a highly sophisticated and complex subject, and readers who wish to delve into the theory and the design of thermal imaging systems are referred to the books listed in the bibliography section. The bibliography includes also a listing of periodicals and reports dealing with applications of thermography to nondestructive testing.

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Yet from those flames

No light, but rather darkness visible.

Milton

ELEMENTS OF THERMOGRAPHY FOR NONDESTRUCTIVE TESTING

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This paper presents an elementary review of thermal imaging systems, with emphasis on the application of thermography to nondestructive testing. Topics discussed include heat radiation theory; early and contemporary thermal imaging systems; performance characteristics; effects of emissivity, background temperature, atmosphere, and field of view. Examples of various applications of thermography to nondestructive testing are given. A bibliography is included.

Key words: heat; imagery; infrared; nondestructive testing; passive; radiation; remote sensing; temperature; thermography.

1. Introduction

All objects continually emit thermal radiation from their surfaces. Usually the radiation is in the infrared portion of the spectrum, which is not visible to the unaided eye. Indeed, the radiation from an object does not become visible until its temperature exceeds 800 K.

The radiant energy emitted from a heated surface per unit time--i.e., the power radiated--depends on the nature of the surface, on its area, and on its temperature, in accordance with the Stefan-Boltzman law,

$$W = A \varepsilon \sigma T^4 ,$$

where W is the power radiated [watt]

A is the surface area [meters^2]

ε is the emissivity of the surface (sometimes called emittance)

σ is the Stefan-Boltzman constant = 5.670×10^{-8} watt/m^{2}K^4

and T is the absolute temperature.

The emissivity, ε, is a measure of the radiation efficiency of a body, compared to a perfect radiator at the same temperature; thus, ε (assumed to be wavelength independent) is a dimensionless number lying between zero and unity. For example, for a perfect radiator, termed a blackbody, $\varepsilon = 1$; for copper, $\varepsilon \simeq 0.3$.

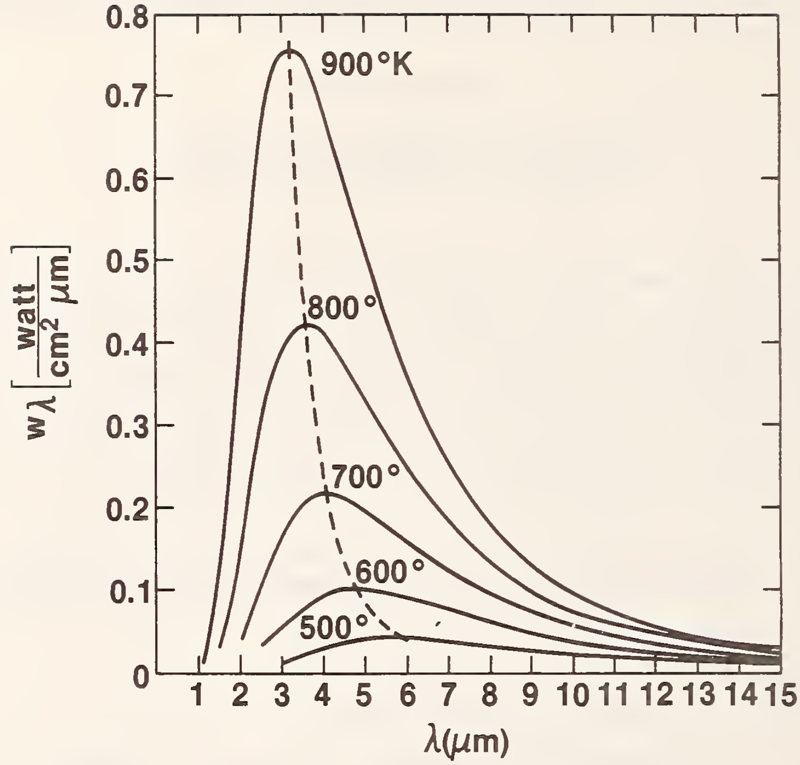


Figure 1. Spectral distribution of blackbody radiant power density at various temperatures. W_λ is the radiant power density per unit wavelength at the wavelength λ.

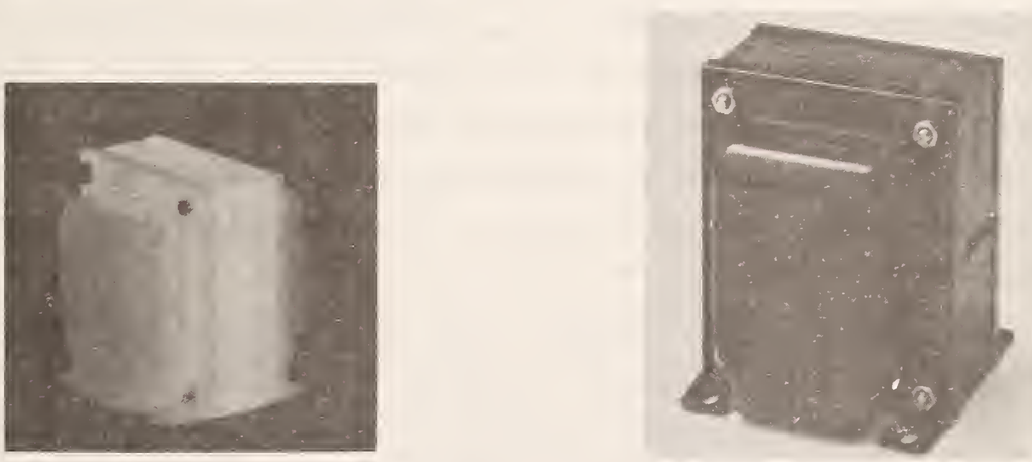
The radiant energy is continually being emitted in the form of a mixture of electromagnetic waves of different wavelengths, and the radiant power is distributed as a continuous function of wavelength. Figure 1 is a graph of the spectral distribution of the radiant power per unit area from the surfaces of several blackbodies of different uniform surface temperatures[1]; here W_λ is the radiant power density per unit wavelength at wavelength λ. Each curve is characterized by a particular wavelength λ_p, a function of temperature, for which W_λ is a maximum. The effect of increasing temperature is seen to shift λ_p to shorter wavelengths, as well as to increase the value of W_λ at each wavelength. The relationship between λ_p and temperature of the maximum W_λ is given by the approximation,

[1]These spectral distribution curves are obtained from Planck's blackbody radiation law. The area under a curve, the total power density radiated, would correspond to the Stefan-Boltzman law, with $\varepsilon = 1$.

$$\lambda_p \simeq 3000/T \, .$$

As a concrete example of spectral distribution of radiant power, a terrestrial object, commonly at $\sim$ 300 K, emits in the 2 μm to 100 μm region, most of the power is in the 3 μm to 14 μm region, and the power peaks at $\sim$ 10 μm. On the other hand, for an incandescent filament at $\sim$ 3000 K, $\lambda_p \simeq 1$ μm, which is in the near infrared. The filament can be seen to be glowing because of the shorter wavelengths emitted in the visible region of the spectrum (approximately 0.38 μm to 0.77 μm).

Although infrared radiation is invisible to the unaided human eye, various means have been devised for detecting and imaging an infrared scene for visualization. Infrared imaging may be classified as active or passive according to whether the scene is irradiated with an infrared source and the resultant reflected radiation is imaged, or whether the self-radiation from the scene is imaged. The latter process, which converts the temperature pattern of a scene into a corresponding contrast pattern, is termed thermography, and the viewed image is termed a thermogram; an example is shown in figure 2(a), a thermogram taken of a current-carrying transformer. For comparison, figure 2(b) is an ordinary photograph of the same current-carrying transformer.



(a) (b)

Figure 2. (a), Thermogram of a current-carrying transformer wherein the light regions signify higher temperatures.

(b), An ordinary photograph of the transformer.

Thermography's ability to see scenes, objects, and features otherwise invisible--sometimes even below a surface--has made it a potent means used in a variety of applications for military, medical, industrial, agricultural, geological, meteorological, and energy conservational purposes. For example, it is used for military intelligence gathering, early warning systems, and weaponry fire control; for medical diagnosis of tumors and inflammations; for monitoring nuclear reactor steam cooling towers; for inspecting refractory linings of furnaces and ducts; for inspecting electrical power transformers and electrical rotating machines while under power; for studying soil moisture, crops, and vegetation decay; for studying volcanoes, glaciers, tides, and tectonic plates, and for detecting petroleum and mineral deposits; for detecting and mapping thermal effluent discharges; and for detecting heat losses from residential buildings, plants, and machinery. These are just some of the myriad ways thermography is being put to use. They are mentioned here only to suggest scope and usefulness, but will not be elaborated on, as this paper is concerned chiefly with the applications of thermography to nondestructive testing.

2. Thermal Imaging Systems

John W. Herschel (son of William, the discoverer of the infrared spectrum) is credited [1,2][1] with inventing thermography in 1840, by utilizing differential evaporation of thin liquid films. This rudimentary apparatus was the prototype for the Evaporograph, as later (1929) Czerny improved on the concept by substituting thin oil films that changed color with differential evaporation resulting from the heat of the incident infrared radiation [2]. And in 1959, the Evaporograph was utilized for qualitative nondestructive testing of hot spots. However, this imaging device was crude and insensitive, with poor repeatability; it is much more of historical than of practical importance.

An exotic way of producing a thermal image is through the use of certain temperature-sensitive liquid crystals, applied directly to the surface to be examined. This technique is sometimes used to examine aerospace structures [3]. However, liquid crystals exposed to the atmosphere have a short lifetime owing to contamination, and their use is rather restricted.

Thermistors, which are commonly oxidic semiconductors having a large negative temperature coefficient of resistance, also may be utilized as the detector in thermal imaging systems. But thermistors have very long time constants, high 1/f

[1]Figures in brackets indicate the literature references at the end of this paper.

noise necessitating chopping of the radiation, and very long scan-frame times, thus making for inferior real-time display, particularly as regards resolution. For imaging systems, thermistors are of rather limited applicability. Thermistors for thermography find their chief use now in infrared microscopes where the targets are small and the image is produced on a photograph.

Most modern thermal imaging systems use either photon detectors or pyro-electrics, a type of thermal detector, as the infrared sensor which receives the radiation from the scene or the target and converts it into an electrical signal for processing and display.

Photon detectors respond to numbers of photons, hence they are wavelength dependent. Owing to their electronic structure, any given detector responds to only a very narrow range of wavelengths. Photon detectors responsive to infrared radiation generally require cooling to 77 K or below, depending on the nature of the material from which the detector is made. Photon detectors fall into either of two categories, photoconductive or photovoltaic, and either may be used in a thermal imaging system. Photoconductors are homogeneous semiconductors, while photovoltaic detectors are junction or barrier devices. The advantages of the photovoltaic detectors are that they require no application of a voltage bias and do not generate a significant amount of heat as does a photoconductor, and their noise may be somewhat lower than photoconductive detectors made of the same material. However, not all materials are utilizable as photovoltaic detectors. The detectors commonly used in thermal imaging systems are indium antimonide photovoltaic detectors at 77 K, for the 3 μm to 5.6 μm region, and mercury cadmium telluride photoconductive and photovoltaic detectors at 77K, for the 8 μm to 14 μm region. Although a single detector may be used, it is usual to use an array of detectors. In general, single detectors and linear arrays are preceded by an opto-mechanical scanner, which dissects the scene or target bit by bit for sequential reception by the detector(s). Opto-mechanical scanners generally utilize rotating or oscillating mirrors or prisms to generate a rectangular raster--i.e., a line-by-line scan of the scene or target--analagous to the formation of a picture on a television screen. On the other hand, focal-plane mosaics (square arrays of detectors) do not require scanning.

Thermal detectors respond to total radiant power, hence they are relatively wavelength independent, their response often extending to very long wavelengths, up to $\sim$ 100 μm. A particularly attractive attribute of thermal detectors is that they require no cooling. This is not just a convenience; it also reduces size, weight, cost, and complexity, and does not introduce additional noise (microphonics) owing to any refrigerator vibrations. Pyroelectrics are a special class of thermal detector; unlike the others they respond only to a change in temperature, rather than to the temperature itself. Hence, pyroelectric devices need to be panned or nutated, or else the incoming radiation from the scene or target needs to be periodically interrupted, or chopped, as for example, with a rotating toothed wheel. However, pyroelectrics will produce a current, or signal, on cooling, as well as on heating, with the polarity of one opposite to that of the other, so special means are provided in the better systems to overcome the effects of changing scene polarity. The pyroelectric in a thermal-imaging system is generally a thin crystal such as triglycene sulfate (although systems employing polymeric films instead--e.g., of polyvinylidene fluoride--are being developed because of their thinness, cheapness, and superior chemical stability). Pyroelectric thermal-imaging systems are usually of the vidicon type, which means that the scene is imaged on one face of the pyroelectric, thus producing a pattern of localized charges on the poorly-conducting pyroelectric material, the magnitudes of which are read by an electron-beam scanning the opposite face of the pyroelectric, in raster fashion. Pyroelectrics, like photovoltaic detectors, do not require biasing. On the other hand, compared to photon detectors, pyroelectrics, like thermal detectors in general, have lower specific detectivities[1] and longer response times. Thus, while the performance of pyroelectric thermal imaging systems can be quite good, the performance of systems with photon detectors can be better. The main attribute of the pyroelectric system, as already mentioned, is its operability over an extensive range of wavelength, without the necessity of cooling.

Although the heart of a thermal-imaging system is its infrared detector(s), the detector is but one of several interacting subsystems which together comprise a complex system. Figure 3 is a simplified block diagram of a scanning thermal-imaging system. The subsystems are, in general, the following, given in sequence: 1) an optical system for collecting the radiance from the scene or target, spectrally filtering, and focusing it onto the detector(s); 2) a scanning system for "dissecting the scene" or a chopper for modulating the radiance; 3) a detector system including any preamplifiers and ancillary circuitry; 4) a signal processor

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[1]Specific detectivity (D*) is the signal-to-noise ratio of the detector output per unit incident power normalized to a unit sensitive detector area and a unit electrical bandwidth. D* is defined in units of [cm $Hz^{\frac{1}{2}}$/watt].

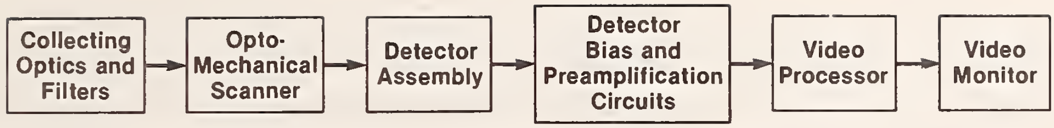

Figure 3. Simplified block diagram of a scanning thermal imaging system.

system for receiving the low-level signal from the detector(s), amplifying it, limiting the bandwidth, extracting the information the signal contains, and delivering this information to the display system; and 5) a display system, generally a video monitor. The signal processor uses techniques similar to that used for commercial television, so 4) and 5) together may be considered a TV system. In addition to the aforementioned subsystems, there may be optical baffles, or stops, to limit field of view and a cooling system such as a dewar, pressurized gas, or heat pump, for cooling the detector(s) and baffles. Because of the complexity and sophistication of the modern thermal-imaging system, it is usually designed by a team of specialists, coordinated by a systems engineer. The fields which are usually represented are radiation theory and radiometry; optical design and engineering, including Fourier optics and optical scanning devices and systems; infrared physics, including detectors, noise theory, and atmospheric transmission; and television engineering.

3. System Performance Characteristics

Thermal images result primarily from temperature differences and/or emissivity differences in a scene or target (rather than reflections), and it is the function of a thermal-imaging system to reproduce an acceptable visible image of the scene or target from its thermal content. Thus, a thermal-imaging system is required to resolve temperature differences and emissivity differences (apparent temperature differences). Further, as temperature and emissivity are distributed spatially in the scene or target, the thermal-imaging system is required to resolve spatial differences of emissivity or temperature. A system's ability to reproduce an accurate, sharp image is given by its performance characteristics, which obviously must include measures of the system's ability to resolve (true and apparent) temperature differences and spatial variations.

Many measures have been devised for characterizing the performance of a thermal-imaging system and its subsystems, with most being of value only as an aid to the subsystem designer or systems engineer. Nevertheless, several measures relating to overall system performance may be of importance to the user of a thermographic system, depending on the application. These measures are 1) [temperature] accuracy[1], 2) noise-equivalent temperature difference [NEΔT or NETD], 3) minimum resolvable temperature difference [MRTD], and 4) minimum detectable temperature difference [MDTD]. Item 1) is relevant to remote radiometric temperature measurements, 2) to temperature sensitivity to a broad area target, and 3) and 4) to imaging. It may be noted that measures 2), 3), and 4) are some expression of temperature difference, which certainly is not surprising. Not obvious, however, is that these temperature differences are functions of signal-to-noise ratio, which also should not be surprising as noise imposes the lower limit of radiative power which may be detected. Each of the above performance measures will now be discussed in relation to their measurement or determination and to their significance and utility.

1) Accuracy -- For most applications of a thermal-imaging system accurate temperature measurements are not of concern, and accuracy is seldom mentioned in thermographic literature or manufacturer's specifications. Further, "highly-accurate" temperature measurements may be exceedingly difficult to make--particularly under some field conditions. Nevertheless, there appears to be a growing need for accurate radiometric temperature determinations, e.g., for process control and for research purposes. Factors which may cause inaccuracy in temperature determination include the original calibration method and inherent operational effects, and effects of atmosphere, emissivity, and reflections (discussed in subsequent sections). If accurate temperature determinations are required, it is generally advisable to make an on-site calibration using blackbody targets of known temperature.[2]

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[1]Some imaging systems include temperature measurement capability, other systems do not.

[2]Note added in proof: A forthcoming paper describes some simple procedures for making qualitative measurements in the field without the need for extensive ancillary equipment. Although the results are not highly accurate, in many cases they are adequate. See Orlove, G. L., Practical Thermal-Measurement Techniques, Proceedings of Thermosense V, SPIE, P.O. Box 10, Bellingham, WA 98227 (to be published).

2) <u>Noise-equivalent temperature difference</u> -- This is a convenient measure of an imaging system's thermal sensitivity to a broad area target whose image completely covers the area of one detector. (Such a target is referred to as an extended source.) If the target is a blackbody at temperature T, and the surrounding background, assumed to be a uniform blackbody, is at temperature T_B, the noise equivalent temperature difference NEΔT is defined as the blackbody target-to-background temperature difference in a standard test pattern which produces a peak signal-to-rms noise ratio (S/N) of unity in the reference electronic filter (used in the processing of the detector signals) when the system views the test pattern. The test pattern can be a square area of temperature greater than the background, as shown in figure 4(a).

Expressed mathematically, noise equivalent temperature difference is given by

$$NE\Delta T = \frac{T - T_B}{S/N} = \frac{\Delta T}{S/N} .$$

When S/N = 1, NEΔT = ΔT. Thus, to measure the noise-equivalent temperature difference, one finds the ΔT which just produces S/N = 1 in the reference electronic filter. Because noise-equivalent temperature difference depends on the filter and on the background temperature, usually ∿ 300 K, these should be specified along with the NEΔT value. The measurement of noise-equivalent temperature difference is not difficult; however, owing mainly to the inaccuracy in measuring rms noise levels, NEΔT is not a very accurate measure. Still, it can be used to compare the thermal sensitivities of two different systems provided the measurements conform to the same standard and the differences in NEΔT are sufficiently large. Thus, for example, if the NEΔT of system A were 0.2°C and that of system B were 0.25°C, both systems would be considered to have essentially the same thermal sensitivity. Alternatively, if the NEΔT of system A were 0.2°C and that of system B under the same conditions were 0.4°C, system A would be considered to be the more sensitive system for those conditions.

Noise-equivalent temperature difference is measured at the video signal output and relates only to the thermal-imaging system exclusive of an image observer. On the other hand, where imagery itself is concerned, an observer's visualization capabilities must be included, as is done for the measures, minimum-resolvable temperature difference (MRTD) and minimum-detectable temperature difference (MDTD), discussed next.

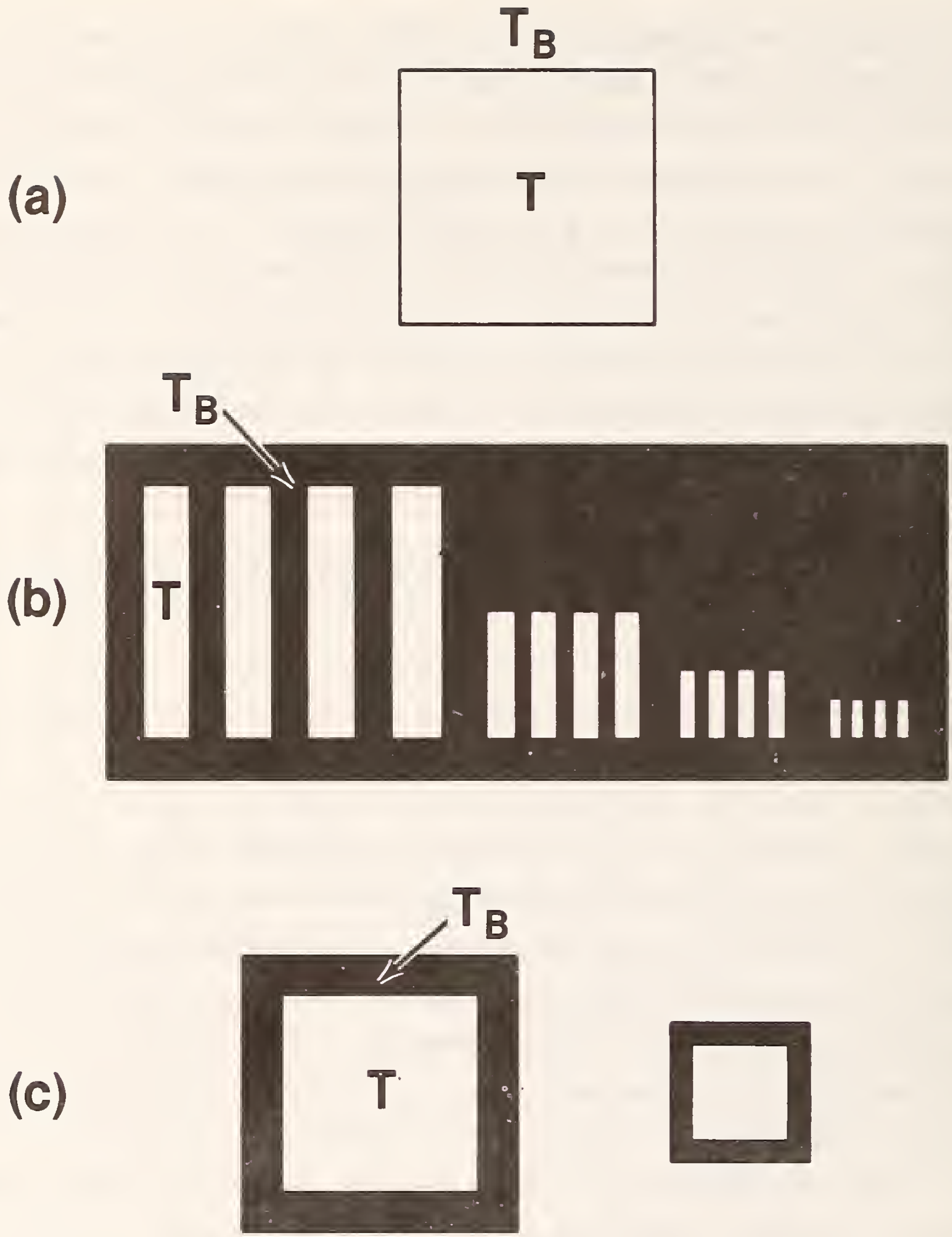

Figure 4. Targets used for measuring performance of thermal imaging systems; T is target temperature, T_B is background temperature, and $T > T_B$. (a), NEΔT. The target is an extended source of square geometry; (b), MRTD. The target is a periodic 4-bar chart of rectangular geometry, with aspect ratio of 7:1; (c), MDTD. The target is a square whose area is equal to the area of the surrounding background temperature.

3) Minimum-resolvable temperature difference -- MRTD is a measure of the compound system-observer capability to spatially resolve temperature differences in a standard target by observing its display on a video monitor. MRTD is a function of target geometry and it is usual practice to use a periodic 4-bar chart of rectangular geometry and aspect ratio (length:width) of 7:1. MRTD is a function also of the periodicity of the bars, or its inverse, the spatial frequency[1], so in practice MRTD is measured as a function of the spatial frequency and shown as a curve. Examples of targets used for these measurements are shown in figure 4(b). The targets are blackbody radiators of different, but uniform temperatures. Further, the power of the eye-brain to resolve spatial temperature differences is a function of signal-to-noise ratio (S/N). For example, the probability of resolution with a standard target is $\sim$ 50 percent for a display S/N of roughly 3 and is $\sim$ 90 percent for S/N $\simeq$ 5. Thus, the probability of detection should be specified along with the MRTD vs. spatial frequency curves.

Qualitatively, MRTD is defined as the image S/N required for an observer to resolve a defined 4-bar pattern chart that is masked by noise, and it is expressed as the temperature difference between the bars and the background.

Analytically, the MRTD is directly proportional to the noise-equivalent temperature difference (NEΔT) of the system and inversely proportional to a mathematical quantity called the modulation transfer function (MTF); hence, MRTD can be derived or it can be measured directly. A brief discussion of the modulation transfer function will now be given in order to make clearer the significance of the minimum resolvable temperature difference.

Consider a target to be decomposed into a vast number of discrete points of various intensities or radiances--which, in fact, is precisely what the opto-mechanical scanner accomplishes. If an imaging system were perfect, every point in the target would be reproduced exactly in the image (with due allowance for any magnification or inversion), and the target would be reproduced exactly by the total image. In reality, perfect fidelity is a physical impossibility, owing mainly to diffraction effects from finite apertures. Examples of finite apertures in imaging systems include lenses, stops, infrared detectors (responsive areas), and the scanning electron beam spot of the display tube. Thus the image

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[1]Spatial frequency may be defined in terms of the angle between an observation point and the normal distance between the centerlines of two adjacent bars. The usual units are cycles/mrad or (number of) lines/picture height.

differs from the object in amplitude (it is attenuated), shape, position, or all three. The modulation transfer function (the modulus of a Fourier transform) gives a spatial description of the attenuation in amplitude; the minimum attenuation is denoted by a normalized MTF of unity.

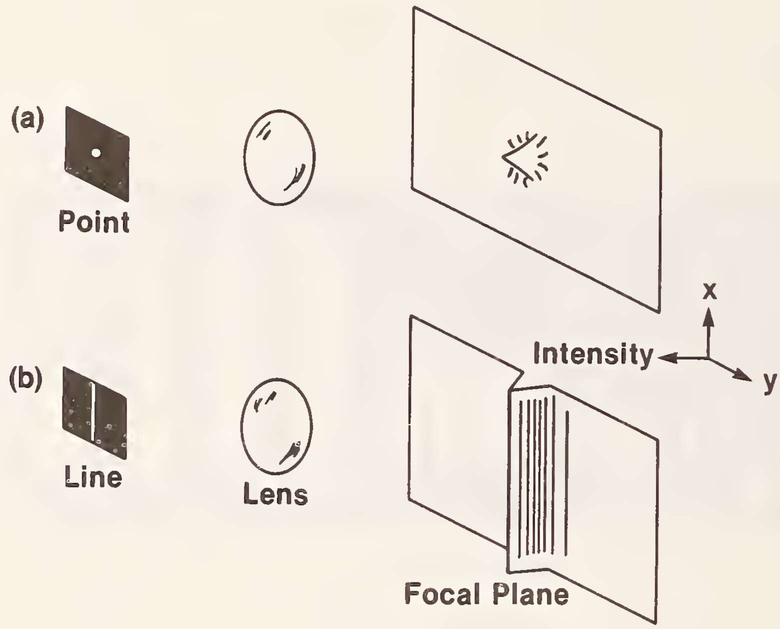

Figure 5. Effect of a finite aperture on the image of a point source (a) and a line source (b).

Figure 5(a) illustrates the effect of the finite aperture of a lens on the image of a point source. If a point source were focused through a thin (negligible refraction), aberration-free, positive lens, the image in the focal plane, parallel to the plane of the lens, would be found to be a spread-out spot of non-uniform intensity (intensity is greatest at the centerpoint) and blurred perimeter. A similar phenomenon would occur if a line source (a rectangular slit of uniform radiance or intensity) were substituted for the point source, as depicted in figure 5(b).

The MTF of the overall thermal imaging system includes the individual MTF's associated with its various apertures and it relates to the ability of the system to recreate the thermal-spatial frequency content of an object. The (system) MTF can be determined by measuring the point or line spread (cf figure 5) from a blackbody source using photometric or thermal techniques, and applying Fourier analysis. (The measurement is quite difficult--aperture dimensions and positions must be precisely determined and temperatures need to be controlled to within ±0.05°C.)

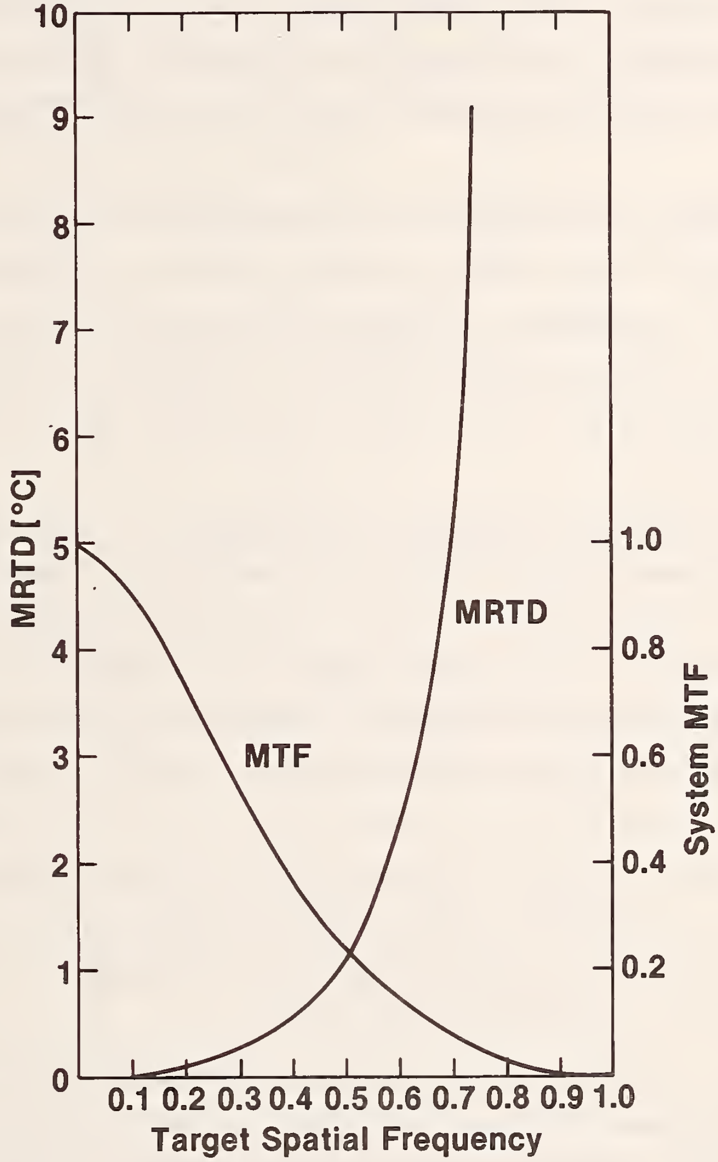

Figure 6. Example of the dependence of minimum resolvable temperature difference (MRTD) and modulation transfer function (MTF) on normalized spatial frequency.

A modulation transfer function, in general, is a sensitive function of spatial frequency, as may be noted in the example of figure 6. MTF decreases with increasing spatial frequency and in fact vanishes at sufficiently high spatial frequency; i.e., the element (aperture) blocks high spatial frequency information.

Remembering that MRTD $\propto$ NEΔT/MTF, the dependence of MRTD on spatial frequency can be graphed, as shown in the example of figure 6, where the system MTF has been included for instructive purposes. The intuitively realizable result shows that the resolution of closely-spaced lines of high spatial frequency requires greater contrast, or temperature difference, between a line and the background, than does widely-spaced lines of low spatial frequency; cf figure 4(b).

Although MRTD is a function of noise-equivalent temperature difference, it is obvious that NEΔT alone cannot be used to compare the performance of two different systems in spatially resolving temperature differences. For example, system A can have a lower (better) NEΔT than system B, but the MTF of B may be sufficiently larger (better) than that of A, so that the MRTD of B is lower (better) than that of A.

4. Minimum-detectable temperature difference -- The minimum-detectable temperature difference (MDTD) is similar to the minimum-resolvable temperature difference, except that instead of the 4-bar pattern, the target consists of a uniformly heated square of blackbody temperature T framed by a uniform background, of specified area, at blackbody temperature T_B; this target is imaged by the system and observed under improved conditions of long search time and known target location. An MDTD target is depicted in figure 4(c); the area of the square of temperature T is equal to the area of the surrounding background of temperature T_B. As for MRTD, curves of MDTD as a function of spatial frequency are obtained, except that spatial frequency is expressed in terms of angle of view [mrad], rather than lines/picture height.

Where details in imagery are of concern, MRTD would be a more useful measure than MDTD; however, where detection of small hot spots in a wide expanse is of concern, as for many nondestructive testing applications, MDTD would be the more useful measure.

Finally, performance measures are useful indicators, and it is hoped that they will correlate with field use, so a caveat is in order. The performance measures are obtained under ideal laboratory conditions such as blackbody targets and unit transmissivity, and the temperature differences are small, < 1°C. Field conditions may deviate appreciably, so performance measures must be utilized cautiously or with modification.

4. The Target and The Image

Thermal-imaging systems act on target information and the contents of an image, including the intelligence therein, depend on characteristics of the target as well as those of the imaging system. The latter has already been treated in some detail; for optimal use of a thermal-imaging system, it is necessary to consider also the characteristics of a target. Some basic facts concerning the target are now listed:

1) The thermal radiation from a target (radiance) emanates from its surface;

2) A thermal-imaging system responds to irradiance at its entrance aperture (which one would like to be only radiance from the target). Thus the imaging system will perceive apparent temperatures or apparent temperature differences present at the surface of the target. If the target is a uniform blackbody, the apparent temperature will be the "true" temperature (neglecting any extraneous effects). If the target is a greybody (an object of uniform emissivity < 1), the apparent temperature will not be the "true" temperature; likewise, the system will indicate emissivity differences as temperature differences.

3) A thermal-imaging system, no matter how good, cannot distinguish a target from its background unless there is sufficient contrast between the target and its background. Contrast is defined as the difference between the radiances of the target L and of the background L_B, divided by their sum $L + L_B$. As the ease with which an object can be identified depends on contrast, it is sometimes desirable to increase the contrast, e.g., by using spectral filters to measure over a limited spectral region, or by suppressing background radiance, a sophisticated and costly measure.

4) Obviously the spectral response of the system's infrared detectors must include the spectral radiance of the target. Optimal detection results when the peaks of both coincide, but optimal detection is not always necessary; mismatches may be compensated by large irradiance or high spectral detectivity.

For convenience, targets may be classified according to 1) emissivity and 2) size relative to image size.

1) If the thermal target is a perfect or near-perfect absorber of radiation over all wavelengths, it is said to be a blackbody, and the emissivity $\varepsilon \simeq 1$. A target of constant emissivity < 1 is said to be a greybody.

2) If the target fills the field of view of the detector (i.e., the image of the target is larger than the area of a single detector), the target is said to be an extended source. If the target does not fill the field of view (i.e., the image of the target is smaller than the area of a single detector), the target is said to be a nonresolvable source (and considered to be a point source).

A consideration of the foregoing will show that it is advantageous to employ targets which are blackbody extended sources:

If the target is an extended source, the radiometric quantity of concern is radiance,

$$L = \frac{W}{\pi}$$

where L is radiance [watt/cm^2 sr],
W is radiant emittance [watt/cm^2].

Ignoring attenuation by the atmosphere or the optics, the irradiance at the sensor is independent of distance to the source, and is given by

$$H = L\omega$$

where H is irradiance [watt/cm^2].

ω is the solid angle subtended by the detector [sr].

When two areas differ in radiance, the difference may be due to a difference in temperature or emissivity, or both, so in general,

$$\Delta L = \Delta L_T + \Delta L_E.$$

If the source is a blackbody

$$\Delta L = \Delta L_T ,$$

and variations in radiance are due only to temperature differences. Therefore, system temperature-sensitivity performance on an actual (as opposed to test) target should correlate with the noise-equivalent temperature difference of the system (which is measured on blackbody test targets).

The noise-equivalent temperature difference may be written

$$NE\Delta T = \frac{H_o}{\omega \tau_a L} ,$$

where H_o is the noise-equivalent irradiance--i.e., the irradiance for which the signal-to-noise ratio is unity, τ_a is the atmospheric transmissivity (assuming negligible atmospheric absorption, $\tau_a = 1$).

It is a property of solids that any material discontinuities in an object--e.g., cracks, fractures, voids, foreign inclusions--will result in a corresponding temperature discontinuity if heat is made to flow through the object. While surface discontinuities may be discernible because of emissivity differences alone, thermal viewing of infrasurface discontinuities requires that heat flow through the target. The required heat may be developed from within the target--as with electrical components or running tires--or from without--as by heat soaking the material just prior to viewing, or by uniformly heating the surface of the material during viewing. To eliminate spurious results due to emissivity differences, it is usual practice to paint or spray the surface with a coating of highly absorbing material, thus approximating a uniform blackbody target.

The temperature discontinuities, or differences, in a heated target may originate at the surface, the subsurface, or in the interior. In any case, thermal radiation is emitted only from the surface, so infrasurface temperature differences must be transmitted to the surface if they are to be perceived by a thermal-imaging system. Whether or not an infrasurface-originating temperature difference--i.e., an infrasurface defect--can be detected depends strongly on its depth and on the thermal conductivity of the target material. If an infrasurface temperature difference is produced, heat will diffuse from the warmer to the cooler regions in all directions, including that of the surface. If the thermal conductivity of the material is low--e.g., ceramics, glass, rubber--the heat will not readily disperse, so that a temperature difference may be transferred to the surface. On the other hand, if the thermal conductivity is high--e.g., metals--heat will readily disperse and the target will soon acquire a uniform equilibrium temperature with no temperature difference manifest at the surface.

At this juncture the reader may wish to review the descriptions of the various targets used for the measurements of performance, and these have been summarized in figure 4. Additionally, recall that a quoted value of NEΔT should include specifications of the background temperature and the reference electronic filter in the measurement circuit, while quoted values of MRTD/MDTD should also include specifications of spatial frequency/angle of view and the probability of resolution/detection.

5. Atmospheric Effects

Atmospheric effects are of great importance in airborne thermography where the source, or target, is far away. The atmosphere may attenuate the radiation from the target, as well as alter its spatial, temporal, and spectral characteristics, thus degrading the target information received. On the other hand, in nondestructive testing atmospheric effects are generally of negligible importance because the source is quite close (< 1 m) and the atmosphere is uncontaminated with vapors such as smoke, fog, etc. Occasionally, however, nondestructive testing may involve critical measurements or may have to be made under adverse conditions--e.g., the source is distant or the atmosphere is humid--such that atmospheric effects need to be considered.

Atmospheric effects arise from (1) the interaction of the atmosphere with the target radiation and (2) from inherent causes. The ways in which atmospheric effects are manifested are

1. Absorption of source radiation by various atmospheric constituents, notably water vapor, carbon dioxide, nitrous oxide, and ozone, of which the first two are prominent. The absorption is selective with optical frequency, resulting in an absorption spectrum, and it is important that the system's infrared detector have spectral response within an atmospheric "window", where absorption is negligible. As noted above, atmospheric absorption (selectively) attenuates the target radiation;

2. Background thermal radiation from these same atmospheric constituents which are strong absorbers;

3. Scattering of the source radiation out of the path of the imaging optics by molecules of the permanent gases and by aerosols;

4. Scattering of unwanted background radiation into the imaging optics by these same permanent gases and aerosols;

5. Turbulence in the atmosphere, or atmospheric optical noise.

The most important of the above phenomena is atmospheric absorption, a complex subject which has received considerable study. The practicable mathematical solution of atmospheric transmission problems requires a mathematical model, of which there are many, and computer aid. For information on some computer programs, see Goodell et al. [4]; for additional discussion on attenuation, and references, see Holter et al. [5], and The Infrared Handbook [6].

In airborne thermography, atmospheric effects may impose a handicap on good imagery which must be coped with, and mathematical methods of modeling are often used for this purpose. Although modeling is probably the best, if not the sole rational means of coping, it can only provide rough estimates because a model is based on assumptions and the implementing data are uncertain. If atmospheric absorption were a problem in nondestructive testing, it would be preferable to calibrate the system on site with the aid of a blackbody target, rather than to employ modeling.

6. Radiometric Measurement of Temperature

The primary function of a thermal imaging system is to obtain a visual image of a thermal target. Additionally, however, some systems may be used for remote determination of target temperature (a minority of sophisticated systems incorporate a blackbody benchmark). Such temperature measurements properly are more in the realm of radiometry than thermography. Nevertheless, the factors of concern are some of the same factors which are of concern in imagery, viz. target, background, and atmospheric effects. The manifestations of the factors differ for the two cases, but unsurprisingly the solutions are the same.

The imaging system, like any radiometric device, responds to the irradiance at its entrance aperture. If the target is unresolved, the irradiance is a function of distance to the target and its temperature is given by [1]

$$T_\mu = \left[\frac{2\, R^2\, (\omega\, \Delta f)^{\frac{1}{2}}}{\sigma\, A_s\, D_o\, (NA)\, D^*\, \tau_a\, \tau_o\, \varepsilon} \cdot \frac{S}{N}\right]^{\frac{1}{4}},$$

where T_μ is temperature [K]

R is distance between target and detector [cm]

ω is solid angle subtended by detector [sr]

Δf is noise equivalent band pass [Hz]

σ is Stefan-Boltzman's constant [W/cm^2K^4]

A_s is target surface area [cm^2]

D_o is lens diameter [cm]

NA is numerical aperture [dimensionless]

D^* is specific detectivity [$cm(Hz)^{\frac{1}{2}}\, W^{-1}$]

τ_a is atmospheric transmittance [dimensionless]

τ_o is spectral transmittance of detector, including the optics [dimensionless]

ε is emissivity [dimensionless]

$\frac{S}{N}$ is signal-to-noise ratio [dimensionless].

If the target is an extended source, the irradiance is independent of the distance to the target, and its temperature T_e is given by [1]

$$T_e = \left[\frac{2}{\sigma\, D_o\, (NA)\, D^*\, \tau_a\, \tau_o\, \varepsilon} \cdot \frac{S}{N}\left(\frac{\Delta f}{\omega}\right)^{\frac{1}{2}}\right]^{\frac{1}{4}}$$

Note that T_e is independent of both target distance and target area, a particularly valuable characteristic that is exploited for industrial process control and for nondestructive testing.

Assuming errors in system calibration to be negligible, the potential sources of error in temperature determination are emissivity variations, atmospheric effects, and background effects. These have already been discussed in connection with imagery, and those discussions generally carry over.

Nevertheless, some additional remarks concerning background effects are worth noting here. As alluded to, above, background is not restricted to the backdrop; background in general encompasses the entire surround that interferes with the radiation being received from the target: atmospheric scattering and emission, radiation from walls and windows, etc. Background radiation which falls on a greybody target will be reflected. Assuming the target to be opaque, the reflectivity, or fraction of the impinging radiation reflected, is merely $(1-\varepsilon)$. The reflected background radiation results in errors in apparent radiance, hence temperature measurement. For a treatment of errors in passive infrared imaging systems due to reflected ambient flux, see J. C. Richmond [7]. On the other hand, if the target is a blackbody, it will absorb all of the impinging background radiation and none will be reflected. Thus it is practice in nondestructive testing, to coat targets such that they are rendered blackbodies. In sum, there are many advantages to working on blackbody extended sources, rather than greybodies or unresolved sources, whether for imagery or for radiometry. For references to various calibration techniques for radiometers, see Hudson [1], p. 437 (10-15).

7. Applications of Thermography to Nondestructive Testing

Early on, it became apparent that the infrared radiative properties of matter were exploitable, especially militarily. Thus, heat seeking devices for searching and tracking were already being proposed in 1910. The desire for new and improved military capabilities, augmented by monetary support, has been the impetus and the nurture for infrared technology in general, and thermography in particular. Modern commercial imaging systems are a modified spillover.

Use of thermography for nondestructive testing dates back several decades. The main application then, as now, was the qualitative detection and location of hot spots, indicators of incipient failure. As technology advanced, however, and more sophisticated imaging systems became available, their application to nondestructive testing followed suit, and the realm of work expanded into quantitative determinations, especially important for process control and strength of materials.

Hudson's [1] section 17.4.1 provides an annotated listing of accessible published literature, covering the years 1946-1977, dealing with the thermographic application to nondestructive testing and inspection. Many of these papers deal with electronic applications such as the detection of overheated components on circuit boards. There are also papers on the detection of delaminations, voids, undesired inclusions, and cracks in motor casings; bonds; weldments; anti-icing panels; and thermal insulation. Closely allied with thermography as a tool for nondestructive testing, inspection, and process control is radiometry, and Hudson's section 17.2.1 gives an annotated listing of pertinent references.

The September 1968 issue of Applied Optics [8] is dedicated to nondestructive testing with infrared thermal-imaging devices. Some of the applications reported there are the same as those of the previous listing; other papers report on bonding/debonding of aerospace structures, fatigue cracks, coatings and bonds, lamination/delamination, and incipient failure in power line transformers, motors, embedded heating elements, and electrical connections. These types of application persist.

Some of the later published literature is referenced herein [9-22]. Further, readers may wish to peruse the international journal, NDT, for its research and development articles on nondestructive testing in general, and for its survey of published literature and patents.

It is apparent that the remote sensing capabilities of thermography and radiometry can be used effectively for automatic process control and quality control, and indeed some companies are doing so. Many accounts of such applications are not made public, however, as they are considered to be proprietary.

Finally, in the usual course of events, one is confronted by a problem for which a means of solution is then sought. With the modest background in thermography presented herein, an investigator with an appropriate knowledge of an intended target should be able to make a rational judgment concerning the feasibility of applying themography. Some test objectives are simple and require only a simple instrument (imaging system); others are demanding and require a sophisticated instrument. Further, owing to inaccessibility of adverse targets or extraneous effects, thermographic testing may be complicated, and an alternative method of testing might be better. Usually, however, in the laboratory at least, conditions can be established favorable to the execution of simple and direct nondestructive testing by thermography.

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EPILOGUE

The demands by the military and industrial sectors for new or improved capabilities are giving rise to rapid expansion of thermal-imaging system technology. Military needs for improved imagery, amply supported, are expected to result in replacement of discrete detector arrays by monolithic charge coupled devices (CCD), and to detector materials with broader spectral response capabilities; these improvements should ultimately enter the civilian market. In industry, the application of thermography to plant monitoring (preventive maintenance), process control, robotics, and nondestructive testing is widespread and growing rapidly as increasing numbers of industries and plants are recognizing both the capabilities and the cost benefits to be derived. Although qualitative thermography--the detection of thermal gradients or hot spots--is still the usual industrial requirement, there is increasing demand for quantitative thermography--the size and location of defects--as well as for the accurate determination of temperature, especially for process control where temperature is a critical parameter.

This introductory work is a simplified treatment of a subject which can be highly complex and esoteric. The report has aimed to familiarize the reader with the broad aspects of thermography and to make him aware of various factors which may have to be considered in the application of thermography. On the other hand, this report does not attempt to solve the various problems which can arise--indeed, this would require a major work of encyclopedic dimensions--and the enterprise must reside with the needful reader. Those who intend to pursue thermography as a career or require additional information might initially consult the references and bibliography given herein.

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This paper presents an elementary review of thermal imaging systems, with emphasis on the application of thermography to nondestructive testing. Topics discussed include heat radiation theory; early and contemporary thermal imaging systems; performance characteristics; effects of emissivity, background temperature, atmosphere, and field of view. Examples of various applications of thermography to nondestructive testing are given. A bibliography is included.

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