Infrared Thermography Field Application Guide

TR-107142

Final Report, January 1999

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REPORT SUMMARY

Infrared thermography (IR) is widely used by utilities as part of a predictive maintenance program for inspection of a variety of plant mechanical and electrical components. The non-contact, remote inspection capabilities of this technology make it extremely appealing for on-line, in-service inspection applications. By observing and analyzing the thermal signature of an operating component, the thermographer is able to provide valuable information about the continued operability of that component.

Implementation and maintenance of an Infrared Thermography program have provided utilities with tremendous paybacks in the form of lowered operating costs and improved availability. Continued expansion of these programs to include additional components will yield additional benefits.

Background

EPRI Report NP-6973s, *Infrared Thermography Guide, Revision 2*, provides guidance to the utility thermographer for using IR as a predictive maintenance tool. It provides information on the IR theory of operation, IR equipment operation and selection, inspection techniques, inspection application examples, training and certification, and key elements of an in-house IR program.

This report, *Infrared Thermography Field Application Guide,* provides supplemental information that is not covered in the IR guide.

Objective

To provide supplemental information (regarding IR applications) for electrical transmission and distribution lines, substations, and nondestructive testing.

Approach

Information for inclusion in the *Infrared Thermography Field Application Guide* was solicited from utility thermographers and other recognized industry experts. General information and specific examples are presented for each application area. It is intended that the information presented in this report will supplement the previously released *Infrared Thermography Guide, Revision 2.*

Results

This report provides a brief review and refresher tutorial on heat flow basics and infrared radiation theory, along with a tutorial on infrared nondestructive inspection using passive and active IR techniques. The IR applications for substation and transmission and distribution lines are discussed in terms of key requirements for a successful program and are supplemented with sample images.

EPRI Perspective

Infrared thermography has been proven to be a valuable predictive maintenance tool for utility inspection programs. This report also illustrates how IR is developing as a tool for nondestructive inspection. Utility IR programs are continually growing in scope and effectiveness. By providing guidance for the implementation of proven IR techniques and by exploring the feasibility of newly developed techniques, utilities can continue to improve plant performance and availability.

Interest Categories

Non-destructive examination
Fossil steam plant O&M cost reduction
Substation O&M

Keywords

Infrared thermography
Predictive maintenance

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1

INTRODUCTION

The purpose of this document is to provide direction and guidance to EPRI member utility personnel pursuing systematic Infrared Thermographic programs in any one of three specific application areas:

Infrared Thermography for Electrical Transmission and Distribution Lines
Infrared Thermography for Electrical Substations
Infrared Thermography for Nondestructive Testing

The currently available EPRI Infrared Thermography Guide, Revision 2 (NP-6973s, Rev. 2), provides guidance for performing IR Thermography programs within plants and generating facilities. The three application areas listed above are mentioned in the EPRI Guide but are not covered in depth as they are in this document. This Application Guide is meant to serve as a supplement to the EPRI Guide. References to the Guide will be found throughout this document.

1.1 Overview of Contents

Chapter 2 provides a brief review and refresher tutorial on heat flow basics and infrared radiation theory. It reviews interpretation of thermal images and their relationship to product quality and the operational status of operating equipment. The basics of Infrared Nondestructive Evaluation (IRNDE) are introduced and the concepts of passive and active IRNDE techniques are reviewed.

Chapter 3 provides an overview of current common practice for the performance of IR inspections on electrical transmission and distribution lines (T&D) and in electrical substations. This includes inspection equipment and accessories requirements, personnel qualifications and training, inspection parameters, components inspected, report preparation, and safety considerations.

Chapter 4 presents representative thermal images for T&D and substation components.

Chapter 5 provides a review of currently employed active thermographic techniques for IRNDE of materials and products. It includes discussions of various forms and mechanisms for heat/cold injection, fixturing and accessories, performance parameters

of IR equipment used, image processing software and techniques, and operator interaction.

Chapter 6 presents case histories and sample reports from inspection programs involving active IRNDE. It also provides a perspective on advantages, disadvantages and current limitations of this technique.

Chapter 7 contains a list of references for additional information.

2

THEORY AND PRACTICAL APPLICATIONS

OVERVIEW

The information on heat flow and infrared sensing basics provided in this chapter is intended to be a refresher tutorial on these subjects. A more thorough discussion on these subjects is provided in the EPRI *Infrared Thermography Guide, Revision 2,* (NP-6973s Rev. 2,) Appendix A [1], and additional references can be found in Chapter 7 of this document.

Infrared thermography is based on measuring the distribution of radiant thermal energy (one form of heat) emitted from a target surface and converting this to a surface temperature map or thermogram. The thermographer needs an understanding of heat, temperature, and the various types of heat transfer as an essential prerequisite in preparing to undertake a program of IR thermography. The following discussion on heat flow is to provide the reader with a basic understanding of how heat transfer phenomena affect non-contact infrared thermal sensing and thermographic measurements.

2.1 Heat Flow

Heat is thermal energy in transition. Like all other forms of energy, heat can neither be created nor destroyed. It can, however, be converted to and from other forms of energy such as electrical energy (in heat pumps, thermoelectric devices, and steam generators) and kinetic energy (in steam engines and rotating devices producing friction). What might appear to be a source creating heat, such as an electrical space heater, is really a mechanism converting energy from one form (electrical) to another (heat).

Heat is dynamic, that is, it resists stability. It always flows "thermally downhill", from points of higher temperature to points of lower temperature. Maintaining a body or a surface at a stable temperature within a constantly changing environment requires the continuous insertion (or removal) of heat or some other form of energy that is converted to heat.

Temperature is, therefore, one way of keeping track of heat flow, even though it does not define the entire dynamic thermal condition.

2.2 Temperature and Converting Temperature Units

Temperature is expressed in either absolute or relative terms. There are two absolute scales called "Rankine" (English system - symbol R) and "Kelvin" (metric system - symbol K). There are two corresponding relative scales called "Fahrenheit" (English system - symbol °F) and "Celsius" or "Centigrade" (metric system - symbol °C). The conversion factors are summarized as follows:

$$T_{Celsius} = 5/9\,(T_{Fahrenheit} - 32)$$

$$T_{Fahrenheit} = 9/5\,T_{Celsius} + 32$$

$$T_{Rankine} = T_{Fahrenheit} + 459.7$$

$$T_{Kelvin} = T_{Celsius} + 273.16$$

Absolute zero (zero R = zero K) is equal to -273.1°C and is also equal to -459.7°F.

To convert changes in temperature or "ΔT" between the English and Metric systems the simple 9/5 (1.8 to 1) relationship is used:

$$\Delta T_{Fahrenheit\ (or\ Rankine)} = 1.8 \times \Delta T_{Celsius\ (or\ Kelvin)}$$

Table 2-1 is a conversion table, reprinted from the EPRI *Infrared Thermography Guide, Revision 2,* (NP-6973s, Rev. 2), to allow for the rapid conversion of temperature between Fahrenheit and Celsius values. Instructions for the use of the table are shown at the top.

Table 2-1
Temperature Conversion Chart

Instructions for Use:

1. Start in the "Temp." column and find the temperature you wish to convert.
2. If the temperature to be converted is in degrees °C, scan to the right column for the degrees °F equivalent.
3. If the temperature to be converted is in degrees °F, scan to the left column for the degrees °C equivalent.

°C	Temp.	°F	°C	Temp.	°F	°C	Temp.	°F
-101	-150	-238	-36.7	-34	-29.2	-26.7	-16	3.2
-95.6	-140	-220	-36.1	-33	-27.4	-26.1	-15	5
-90	-130	-202	-35.6	-32	-25.6	-25.6	-14	6.8
-84.4	-120	-184	-35	-31	-23.8	-25	-13	8.6
-78.9	-110	-166	-34.4	-30	-22	-24.4	-12	10.4
-73.3	-100	-148	-33.9	-29	-20.2	-23.9	-11	12.2
-67.8	-90	-130	-33.3	-28	-18.4	-23.3	-10	14
-62.2	-80	-112	-32.2	-26	-14.8	-22.8	-9	15.8
-56.7	-70	-94	-31.7	-25	-13	-22.2	-8	17.6
-51.1	-60	-76	-31.1	-24	-11.2	-21.7	-7	19.4
-45.6	-50	-58	-30.6	-23	-9.4	-21.1	-6	21.2
-40	-40	-40	-30	-22	-7.6	-20.6	-5	23
-39.4	-39	-38.2	-29.4	-21	-5.8	-20	-4	24.8
-38.9	-38	-36.4	-28.9	-20	-4	-19.4	-3	26.6
-38.3	-37	-34.6	-28.3	-19	-2.2	-18.9	-2	28.4
-37.8	-36	-32.8	-27.8	-18	0.4	-18.3	-1	30.2
-37.2	-35	-31	-27.2	-17	1.4	-17.8	0	32

Table 2-1 (cont.)
Temperature Conversion Chart

°C	Temp.	°F	°C	Temp.	°F	°C	Temp.	°F
-17.2	1	33.8	-2.8	27	80.6	11.7	53	127.4
-16.7	2	35.6	-2.2	28	82.4	12.2	54	129.2
-16.1	3	37.4	-1.7	29	84.2	12.8	55	131
-15.6	4	39.2	-1.1	30	86	13.3	56	132.8
-15	5	41	-0.6	31	87.8	13.9	57	134.6
-14.4	6	42.8	0	32	89.6	14.4	58	136.4
-13.9	7	44.6	0.6	33	91.4	15	59	138.2
-13.3	8	46.4	1.1	34	93.2	15.6	60	140
-12.8	9	48.2	1.7	35	95	16.1	61	141.8
-12.2	10	50	2.2	36	96.8	16.7	62	143.6
-11.1	12	53.6	2.8	37	98.6	17.2	63	145.4
-10.6	13	55.4	3.3	38	100.4	17.8	64	147.2
-10	14	57.2	3.9	39	102.2	18.3	65	149
-9.4	15	59	4.4	40	104	18.9	66	150.8
-8.9	16	60.8	5	41	105.8	19.4	67	152.6
-8.3	17	62.6	5.6	42	107.6	20	68	154.4
-7.8	18	64.4	6.1	43	109.4	20.6	69	156.2
-7.5	19	66.2	6.7	44	111.2	21.1	70	158
-6.7	20	68	7.2	45	113	21.7	71	159.8
-6.1	21	69.8	7.8	46	114.8	22.2	72	161.6
-5.6	22	71.6	8.3	47	116.6	22.8	73	163.4
-5.0	23	73.4	8.9	48	118.4	23.3	74	165.2
-4.4	24	75.2	10	50	122	23.9	75	167
-3.9	25	77	10.6	51	123.8	24.4	76	168.8
-3.3	26	78.8	11.1	52	125.6	25	77	170.6

Table 2-1 (cont.)
Temperature Conversion Chart

°C	Temp.	°F	°C	Temp.	°F	°C	Temp.	°F
25.6	78	172.4	54.4	130	266	193	380	716
26.1	79	174.2	60	140	284	199	390	734
26.7	80	176	65.6	150	302	204	400	752
27.2	81	177.8	71.1	160	320	210	410	770
27.8	82	179.6	76.7	170	338	216	420	788
28.3	83	181.4	82.2	180	356	221	430	806
28.9	84	183.2	87.8	190	374	227	440	824
29.4	85	185	93.3	200	392	232	450	842
30	86	186.8	98.9	210	410	238	460	860
30.6	87	188.6	104	220	428	243	470	878
31.1	88	190.4	110	230	446	249	480	896
31.7	89	192.2	116	240	464	254	490	914
32.2	90	194	121	250	482	260	500	932
32.8	91	195.8	127	260	500	288	550	1022
33.3	92	197.6	132	270	518	316	600	1112
33.9	93	199.4	138	280	536	343	650	1202
34.4	94	201.2	143	290	554	370	700	1292
35	95	203	149	300	572	399	750	1382
35.6	96	204.8	154	310	590	427	800	1472
36.1	97	206.6	160	320	608	454	850	1562
36.7	98	208.4	166	330	626	482	900	1652
37.2	99	210.2	171	340	644	510	950	1742
37.8	100	212	177	350	662	538	1000	1832
43.3	110	230	182	360	680	566	1050	1922
48.9	120	248	188	370	698	593	1110	2012

Table 2-1 (cont.)
Temperature Conversion Chart

°C	Temp.	°F	°C	Temp.	°F	°C	Temp.	°F
621	1150	2102	843	1550	2822	1066	1950	3542
649	1200	2192	871	1600	2912	1093	2000	3632
677	1250	2282	899	1650	3002	1149	2100	3812
704	1300	2372	927	1700	3092	1204	2200	3992
732	1350	2462	954	1750	3182	1260	2300	4172
760	1400	2552	982	1800	3272	1316	2400	4352
788	1450	2642	1010	1850	3362	1371	2500	4532
816	1500	2732	1038	1900	3452			

Conversion Factors
°C = (°F - 32) x 5/9 0° Kelvin = -273.16 °C
°F = (°C x 9/5) + 32 0° Rankine = -459.69 °F

2.3 The Three Modes of Heat Transfer

Following are the three modes of heat flow or *heat transfer*:

Conduction, where heat flows through a material, usually a solid material, by means of molecular collisions

Convection, where heat is usually carried by a fluid (a liquid or a gas) in motion

Radiation, where heat moves in a manner similar to that of light and at the speed of light, in a straight path, and requiring no medium. (Radiation can take place across a vacuum). Heat radiation occurs in the infrared region of the electromagnetic spectrum.

All heat flows by means of one or more of these modes of transfer. Most often, in the real world, heat flows by all three of these modes in combination.

IR thermography is most closely related to **radiative** heat transfer since infrared thermographic instruments measure the radiated thermal energy from the surface of an object of interest (**the target**). An understanding of **all three modes** of heat transfer, however, is essential in order to carry out a successful thermographic measurements program.

2.3.1 Conductive Heat Flow

Conduction is the transfer of heat in stationary media. It is the only mode of heat flow in solids but can also take place in liquids and gases. It occurs as the result of molecular collisions (in liquids) and atomic vibrations (in solids), whereby energy is moved one molecule at a time from higher temperature sites to lower temperature sites. Figure 2-1 is an illustration of conductive heat flow.

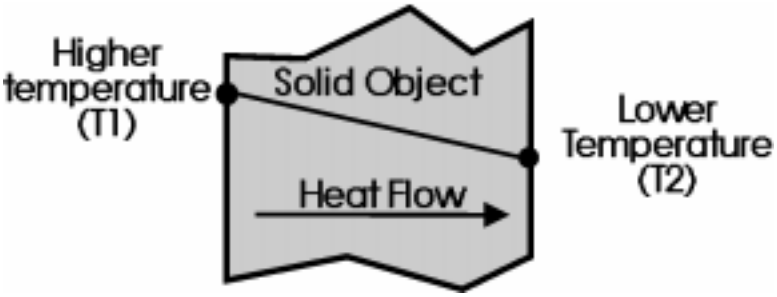


Figure 2-1
Conductive Heat Flow

The rate of conductive transfer through the slab of material shown is directly proportional to the temperature difference and the *coefficient of conductive heat transfer (k)* for that material. It is inversely proportional to the thickness of the material. The mathematical relationships can be found in Appendix A to the EPRI *Infrared Thermography Guide, Revision 2* (NP-6973s, Rev. 2).

Heat flow can be expressed in English units (BTU / ft^2-hr) or metric units (Watts / cm^2-hr)

2.3.2 Convective Heat Flow

Convective heat flow takes place in a moving medium and is almost always associated with transfer between a solid and a moving fluid (such as air). **Forced convection** takes place when an external driving force, such as a wind or an air pump, moves the fluid. **Free convection** takes place when the temperature differences necessary for heat transfer produce density changes in the fluid, and the warmer fluid rises as a result of increased buoyancy.

In convective heat flow, heat transfer takes effect by means of two mechanisms, the direct conduction through the fluid and the motion of the fluid itself. Figure 2-2 illustrates forced convective heat transfer between a flat plate and a moving fluid.

The presence of the plate causes the velocity of the fluid to decrease to zero at the surface and influences its velocity throughout a variable distance called the **boundary**

layer. The thickness of the boundary layer depends on the free velocity, V_f, of the fluid. It is greater for free convection and smaller for forced convection. The rate of heat flow depends, in turn, on the thickness of the convection layer as well as the temperature difference between T_s and T_∞ (T_s is the surface temperature, T_∞ the free field fluid temperature outside the boundary layer). The mathematical relationships involved can be found in Appendix A to the EPRI *Infrared Thermography Guide, Revision 2* (NP-6973s, Rev. 2).

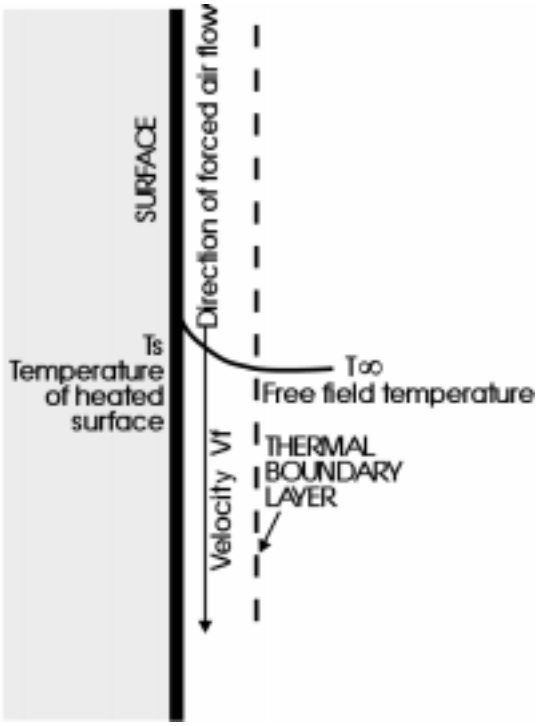


Figure 2-2
Convective Heat Flow Between a Heated Surface and Moving Air

2.3.3 Radiative Heat Flow

Radiative heat transfer takes place in the infrared portion of the spectrum, between 0.75µm and about 100µm, although most practical measurements can be made out to only about 20µm. (**µm** stands for micrometers or "microns". A micron is one-millionth of a meter and is the measurement unit for radiant energy wavelength.)

Radiative heat transfer is unlike the other two modes in several respects:

- It can take place in a vacuum.
- It occurs by electromagnetic emission and absorption.

- It occurs at the speed of light.
- While conductive and convective heat transferred between points is linearly proportional to the temperature difference between them, the energy radiated from a surface is proportional to the fourth power of its absolute temperature. The energy transferred between two surfaces is proportional to the third power of the temperature difference between the surfaces.

2.3.4 The Infrared Spectrum

The measurement of thermal infrared radiation is the basis for non-contact temperature measurement and thermal imaging (or thermography). The electromagnetic spectrum is illustrated in Figure 2-3.

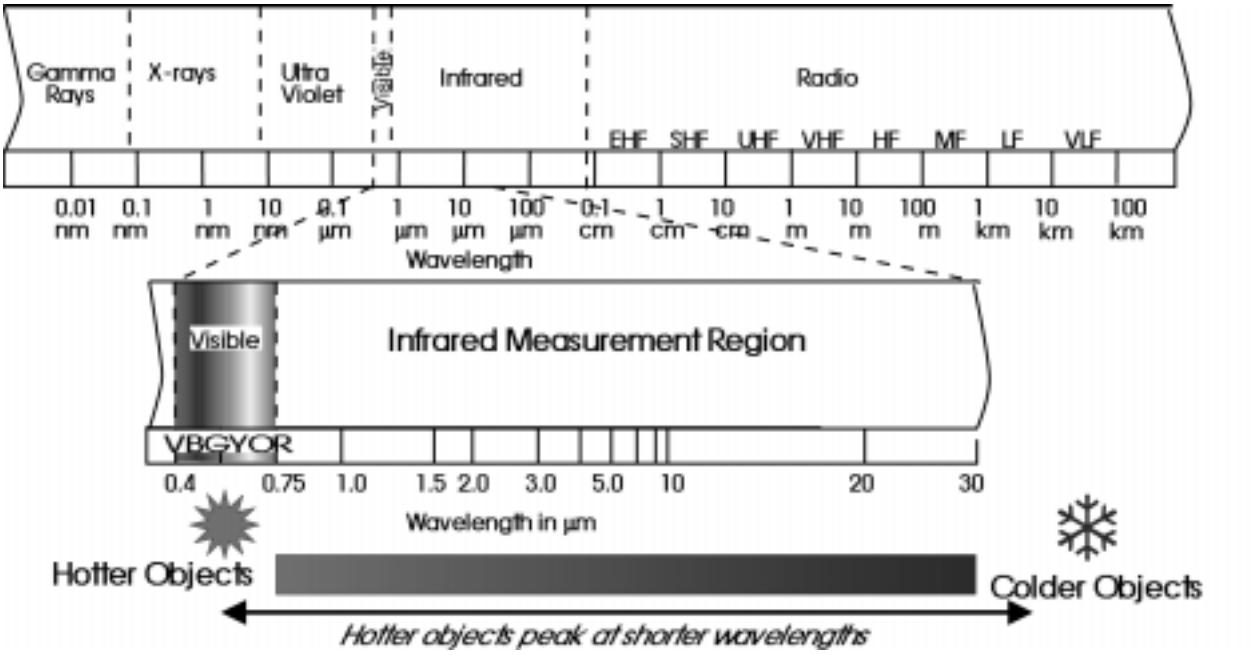


Figure 2-3
The Location of Infrared Radiation in the Electromagnetic Spectrum

The infrared region of the electromagnetic spectrum ranges from approximately 1-1000µm, just above the visible light region. Currently all commercial infrared thermal imagers operate in either the 2-5 µm or the 8-12 µm spectral region, depending on the spectral sensitivity range of the detector used.

Thermal infrared radiation leaving a surface is called **exitance** or **radiosity**. It can be emitted from the surface, reflected off the surface, or transmitted through the surface. This is illustrated in Figure 2-4. The total radiosity is equal to the sum of the emitted

component, W_e, the reflected component, W_r, and the transmitted component, W_t. The surface temperature, however, is related **only** to $\mathbf{W_e}$, the emitted component.

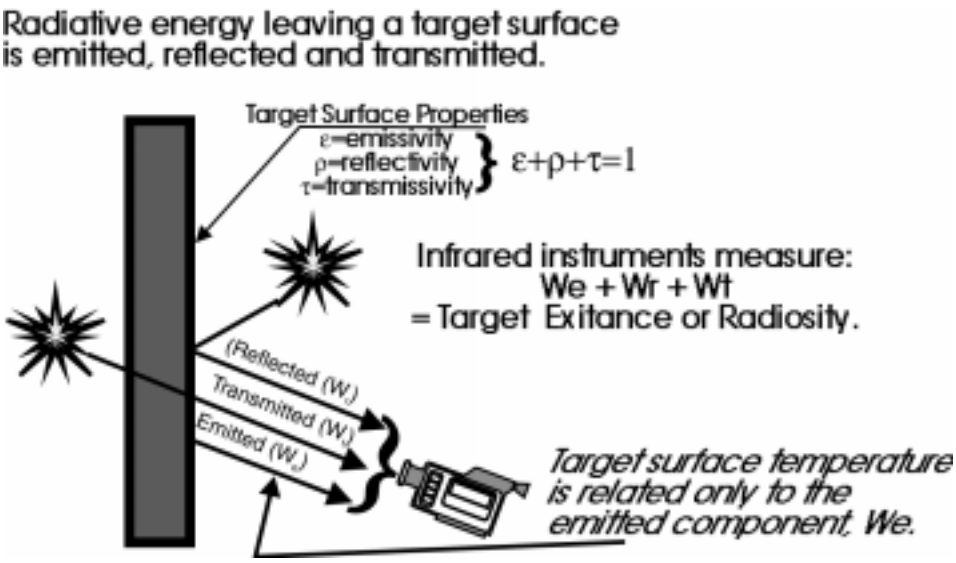


Figure 2-4
Thermal Infrared Radiation Leaving a Surface

2.4 Practical Infrared Measurements: Three Sets of Characteristics

In practical measurement applications, the radiant energy leaves a **target surface**, passes through some **transmitting medium**, usually an atmospheric path, and reaches a **measuring instrument**.

Therefore, in making a measurement or producing a thermogram, the following three sets of characteristics need to be considered, as illustrated in Figure 2-5:

- Characteristics of the target surface
- Characteristics of the transmitting medium
- Characteristics of the measuring instrument

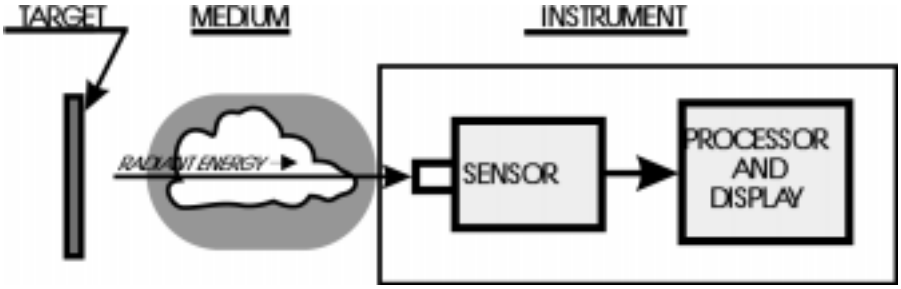


Figure 2-5
Three Sets of Measurement Conditions in IR Thermography

2.4.1 Infrared Characteristics of Targets

Every target surface above absolute zero radiates energy in the infrared. The hotter the target, the more radiant infrared energy is emitted. The physical laws that define this behavior are discussed in detail in Appendix A to the EPRI *Infrared Thermography Guide, Revision 2* (NP-6973s, Rev. 2). The proportion of the radiant infrared energy that is emitted from a surface, reflected off the surface, and transmitted through the surface, depends on the infrared characteristics of the surface. As shown in Figure 2-4, the sum of the material surface characteristics ε (emissivity), ρ (reflectivity), and τ (transmissivity) equals unity (1.0).

It is important for thermographers to understand that, as mentioned previously and illustrated in Figure 2-4, the temperature of a target surface is related only to the self-emitted component of the radiant exitance. To determine the temperature of the surface, it is usually necessary to eliminate, or compensate for, the reflected and transmitted components. It is also necessary to correct the self-emitted component using the effective emissivity of the target surface.

2.4.1.1 Black Bodies, Gray Bodies and Non-Gray Bodies

The **Stephan-Boltzmann** law is the physical law that relates the energy emitted from a target surface to the surface temperature as follows:

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

where W = radiant flux per unit area ($Watts/cm^2$)

σ= 5.673 x 10^{-12} watts-cm^{-2} K^{-4} (Stephan-Boltzmann constant)

ε= surface emissivity

T= surface temperature in Kelvin

Figure 2-6 illustrates the three types of radiating targets, **black bodies**, **gray bodies,** and **non-gray bodies** and their emitting characteristics**.** The area under each curve represents the radiant flux, **W,** emitted by the surface.

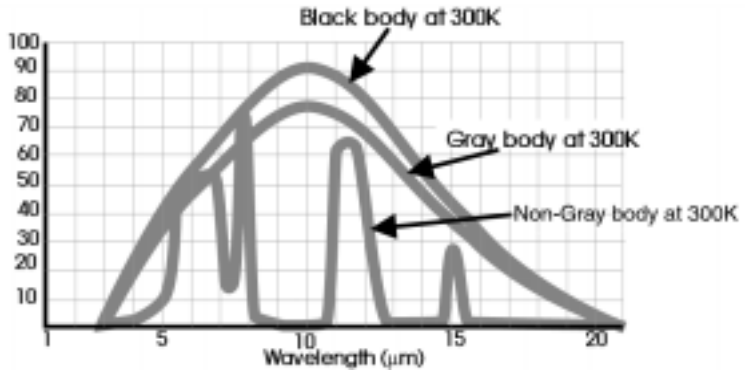


Figure 2-6
How Emitted Radiant Energy is Related to Target Surface Characteristics

- A black body has an emissivity of unity (1.0) at all wavelengths. It reflects and transmits no energy [ρ (reflectivity) and τ (transmissivity) both equal zero]. The total exitance consists of the emitted component only.

- A gray body has an emissivity of less than unity (between 0 and 1.0), which is the same at all wavelengths. It transmits no energy [τ (transmissivity) equals zero]. The total exitance consists of the emitted and reflective components only.

- A non-gray body has an emissivity that varies with wavelength. It might also be partly transparent to infrared energy and, therefore, might transmit infrared energy from sources behind it. The total exitance might include an emitted, a reflected, and a transmitted component.

A black body is a theoretical surface that does not occur in the real world. Most solid, organic or painted surfaces, and oxidized metals are gray bodies with high emissivities. Shiny and polished metal surfaces and some semi-conductor materials are gray bodies with low emissivities and, therefore, high reflectivities. Thin film plastics, glass, gases and many specialty optical materials are non-gray bodies, that is, their emissivities vary with wavelength. A more detailed discussion of infrared characteristics of materials can be found in Appendix A to the EPRI *Infrared Thermography Guide, Revision 2* (NP-6973s, Rev. 2).

2.4.2 The Infrared Characteristics of the Transmitting Medium

Infrared radiation from the target passes through some transmitting medium on its way to the infrared instrument. If the radiation passes through a vacuum, there is no loss of

energy. However, most infrared measurements are made through air. The effect of most atmospheric gases can be ignored for a short distance, such as a few meters. As the path length increases, atmospheric absorption can be a source of error. The spectral transmission characteristics of a 10 meter path of ground level atmosphere at 50% humidity is shown in Figure 2-7. Two spectral intervals are relatively free from absorption losses. These are known as the 3-5µm and the 8-14µm atmospheric "windows," and almost all infrared sensing and imaging instruments are designed to operate in one or the other of these two windows. Most instruments used in IR thermography provide the user with a means for correcting temperature measurements for atmospheric errors by entering the estimated measurement path length into the computation.

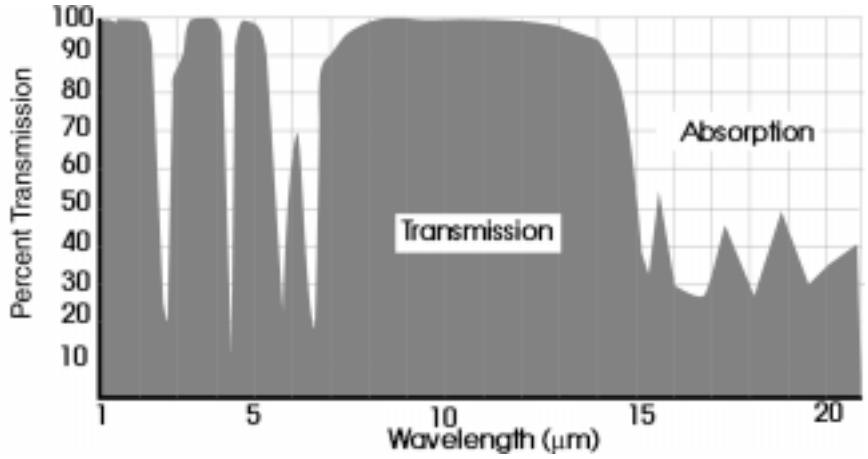


Figure 2-7
Transmission and Absorption of 10 Meters of Ground Level Atmosphere, 50% Humidity

When there is a solid material such as a glass or quartz viewing port between the target and the instrument, such as in some manufacturing processes, again the spectral characteristics of the media must be known and considered. A more detailed discussion of the spectral transmission and absorption characteristics of gases and solid materials can be found in Appendix A of the ERPI *Infrared Thermography Guide, Revision 2, (*NP-6973s, Rev. 2)

2.4.3 Classifications of Infrared Thermal Imagers

There are a wide variety of commercially available infrared thermal sensing and measuring instruments. Of these, **infrared thermal imagers**, also called **infrared cameras,** is the group widely used in infrared thermography. From the user's point of view these instruments are capable of producing **quantitative thermograms** or **qualitative thermograms,** or both.

A **qualitative thermogram** is a map of the infrared radiant exitance of a target surface, uncorrected for the surface characteristics of the target, the absorption of the transmitting medium, or the effect of the ambient environment, that is a rough approximation of the temperature distribution at the target surface.

A **quantitative thermogram** is a map of the infrared radiant exitance of a target surface, corrected for the surface characteristics of the target, the absorption effects of the transmitting medium, and the effect of the ambient environment, so as to approach a true temperature map of the target surface.

Thermal imagers capable of producing only qualitative thermograms are generally known as **thermal viewers**. Thermal imagers capable of producing quantitative as well as qualitative thermograms are generally known as **thermal imaging radiometers**. The various classifications of thermal imagers are listed below.

Qualitative (Thermal Viewers)
- mechanically-scanned
- electronically-scanned (pyroelectric vidicons)
- focal plane array

Quantitative (Thermal Imaging Radiometers)
- mechanically-scanned (scanning radiometers)
- focal plane array radiometers

The list above indicates three configurations of infrared thermal imagers, indicating three approaches to generating a thermal map of a target surface. These are electronic scanning (pyroelectric vidicon), mechanical scanning, and the use of a "staring" infrared focal plane array (FPA).

Figure 2-8 shows the pyroelectric vidicon tube, which is similar to an ordinary, electronically-scanned television camera tube except that it uses a pyroelectric surface sensitive to infrared in the 2-20µm spectral region. The pyrovidicon system is, otherwise, similar to a conventional "camcorder" system.

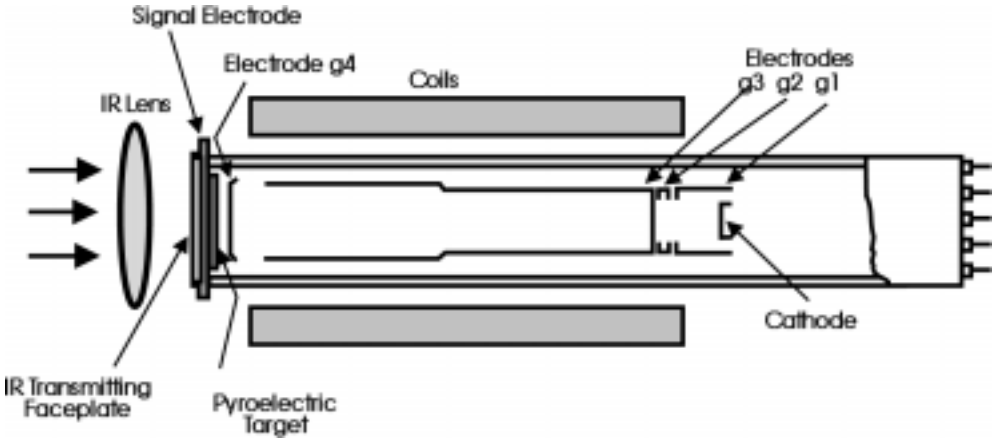


Figure 2-8
Configuration of a Pyroelectric Vidicon Camera Tube
(courtesy of the ISI Group)

Figure 2-9 shows the scanning schematic of a typical mechanically-scanned imaging radiometer, the Inframetrics 760, that employs a single-element detector and galvanometer-driven scanning mirrors.

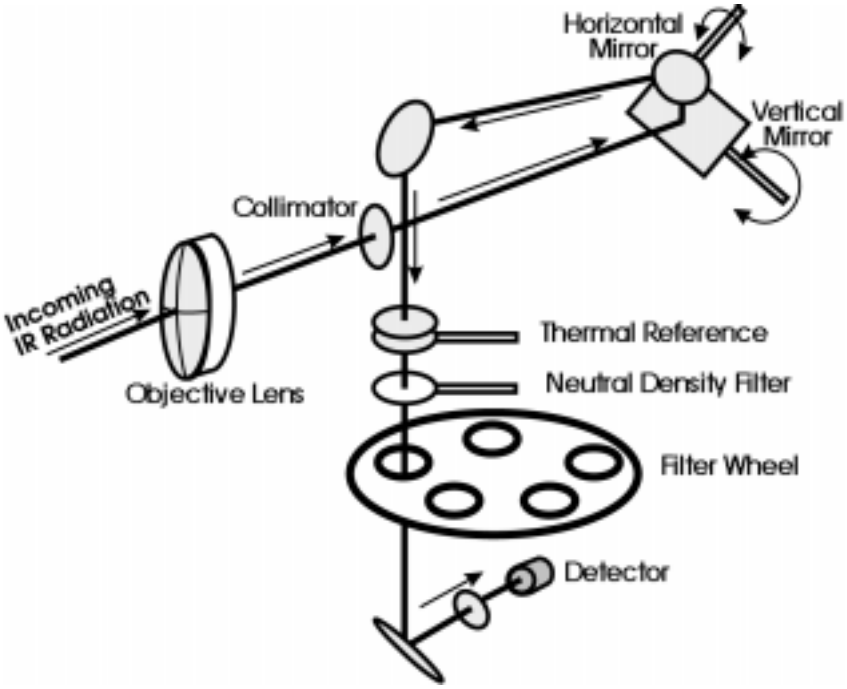


Figure 2-9
Configuration of a Typical Mechanically-Scanned Imaging Radiometer
(courtesy of Inframetrics, Inc.)

Within the past few years, IR thermal imaging instruments based on focal plane detector arrays developed in military and aerospace programs, have become available

to the commercial market. These imagers offer a number of advantages over mechanically-scanned imagers, as will be discussed in the next section. Figure 2-10 illustrates a typical IRFPA instrument configuration.

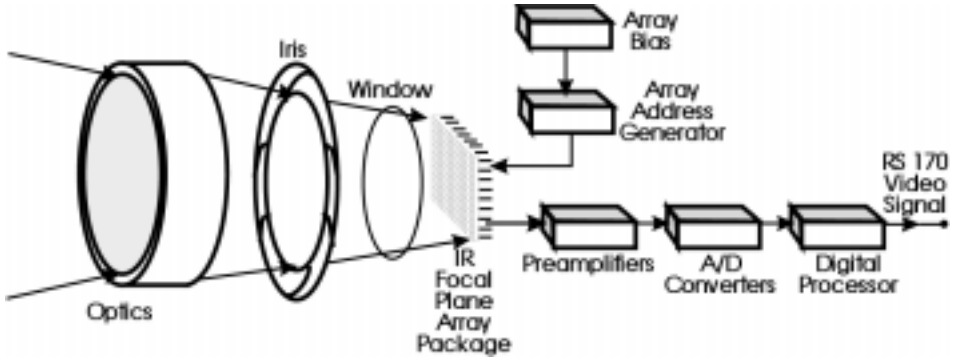


Figure 2-10
Configuration of a Typical IRFPA Imager (courtesy of Honeywell Corp.)

2.4.4 Performance Characteristics of Infrared Thermal Imagers

It is essential for thermographers to understand the performance characteristics of thermal imagers in order to select an appropriate instrument for a project or, more realistically, to understand the limitations of an instrument that happens to be available for the job.

Performance parameters for infrared scanners and imagers are summarized as follows:

- Temperature range(s)
- Absolute measurement accuracy
- Measurement repeatability
- Minimum resolvable temperature (MRT)-temperature sensitivity
- Frame repetition rate
- Total field of view (TFOV)
- Instantaneous field of view (IFOV)-imaging spatial resolution
- Measurement spatial resolution (IFOVmeas)
- Spectral range
- Sensor environment
- Diagnostic software capabilities

Since **thermal viewers** do not measure, those parameters that define measurement capabilities (measurement accuracy and repeatability, and measurement spatial resolution) do not apply. For **imaging radiometers** all of the above parameters should be considered. The following discussions summarize the significance of each of the above parameters. A more detailed discussion can be found in the EPRI *Infrared Thermography Guide, Revision 2,* Appendix A (NP-6973s, Rev. 2).

Temperature Range(s)

This is a statement of the high and low limits over which the target temperature can be measured by the instrument. Most imagers feature a selection of temperature ranges. It is usually expressed in degrees C or F (°C or °F).

Absolute Measurement Accuracy

This refers to the NIST (National Institute for Standards and Technology) temperature reference standard. It describes the maximum error, over the full range, that the measurement will have when compared to this standard blackbody reference. Although all measuring instruments should be periodically calibrated, absolute accuracy is usually not as important as repeatability. It is usually expressed in ±°C or °F, or ± some percent of full scale, or both.

Measurement Repeatability

This describes how faithfully a reading is repeated for the same target under identical measurement conditions, over the short and long term. It is usually more important to the thermographer than absolute accuracy because it is a form of expressing the consistency with which a given instrument performs. It is usually expressed in ±°C or °F or ± some percent of full scale, or both.

Minimum Resolvable Temperature (MRT)-Temperature Sensitivity

This defines the smallest target temperature change at the target surface that can be clearly sensed at the output of the instrument. In the case of an imager, it is the smallest blackbody equivalent target temperature difference that can be observed out of system noise on a thermogram. It is usually expressed in °C or °F.

Frame Repetition Rate

This is defined as the number of times every point on the target is scanned in one second. It is usually expressed in frames per second or Hz. This should not be confused with "field rate". Some scanning imagers are designed to interlace consecutive fields, each consisting of alternate image lines. This results in images that

appear more pleasant to the human eye. The frame rate in this case would be one-half the field rate.

Total Field of View (TFOV)

This defines the image size, in terms of total vertical and horizontal scanning angles, y and x, respectively for any given lens. It is usually expressed in terms of angular degrees in both the horizontal and vertical axes.

Instantaneous Field of View (IFOV)-Imaging Spatial Resolution

This defines the spatial resolution of the instrument. In a radiation thermometer, it is the projection of the sensitive area of the detector at the target plane. In an imager, however, it also represents the size of the smallest picture element that can be imaged. It is usually expressed in the angular cross-section of the spot size (in degrees or milliradians).

Measurement Spatial Resolution (IFOVmeas)

This is similar to the IFOV above except that it defines the minimum target spot size on which an accurate measurement can be made in terms of its distance from the instrument. This is considerably larger than the IFOV for most scanning imagers, and somewhat larger than the IFOV for IRFPA imagers. It is usually expressed in the angular cross-section of the spot size (in degrees or milliradians).

Spectral Range

This defines the portion of the infrared spectrum over which the instrument will operate. Most infrared imaging instruments operate in either the 3-5µm or the 8-12µm spectral region where atmospheric absorption is at a minimum. In some cases, the operating spectral range of the instrument might be critical to its performance and can be exploited to solve difficult measurement problems. The spectral range is determined by the detector and the instrument optics, including the filter.

Sensor Environment

This describes the ambient extremes of temperature, pressure, and humidity under which the instrument will perform within specifications, and the extremes under which it can be stored inoperatively with no subsequent damage.

Diagnostic Software Capabilities

Thermography applications often require the utilization of extensive thermal imaging display and diagnostic software. The new generation of thermal imagers features image

processing capabilities that can be generally categorized into five categories, several or all of which might be used in any specific application. They are:

- Quantitative thermal measurements of targets
- Detailed processing and image diagnostics
- Image recording, storage, and recovery
- Image comparison (differential thermography)
- Database and documentation

These software categories, and the other performance parameters introduced above, are discussed in greater detail in the EPRI *Infrared Thermography Guide, Revision 2,* Appendix A (NP-6973s-Rev. 2).

2.5 How Thermograms Can Reveal Operating Condition or Product Quality

Most operating equipment requires some form of energy to operate. This energy in transition is converted to other forms of energy, including heat. The surface temperature distribution of equipment, therefore, is often a signature of its operating condition. Variations in this signature occur when operating conditions change, particularly when some form of failure mechanism is at work within the equipment. An example of this is illustrated in Figure 2-11. This illustrates normal operation of an air compressor cooling tank, where incoming cooling air (top-center) is mixed with the hot air exhausted from the compressor (left) and the cooled air (right) returns to the compressor. A representative reference point (141°F at the crosshairs) might be chosen, and any subsequent deviation from this temperature would indicate a change in operating condition or a malfunction of the device. The thermal image might be used, after appropriate investigation, as a benchmark to which to compare other similar equipment.

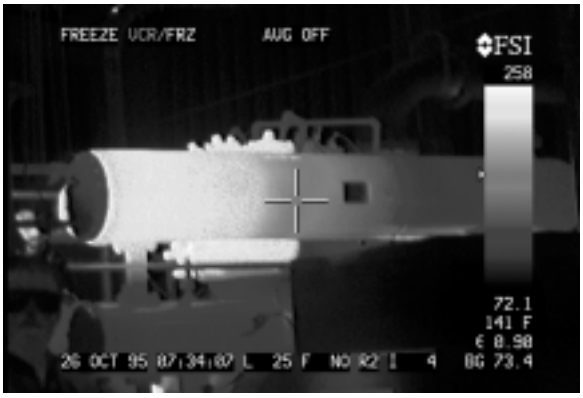


Figure 2-11
Thermogram Showing Normal Operation of an Air Compressor Cooling Tank

The thermogram of a process or a product during manufacture can be used in a similar manner to assess its acceptability. This is illustrated in Figure 2-12, an in-process thermogram of a web of material used to coat gypsum board. In this case the heating at the right-hand edge of the web is due to non-uniformities in the heating process and will result in unacceptable product.



Figure 2-12
Thermogram of Gypsum Board Web Process Showing Out-of-Tolerance Heating at Right

As would be expected, extensive evaluation of thermograms and a thorough investigation of the process and its environment is most often required before the thermal image can be linked reliably to product or process quality. When it is done properly, however, an infrared thermogram becomes an excellent tool for truly ***nondestructive evaluation*** of product and process quality.

2.6 The Passive and Active Approaches to Infrared Nondestructive Evaluation

The above examples illustrate the usefulness of infrared thermograms during the operation of equipment or processes where the surface temperature distribution is a result of the normal operation of the equipment or the process. This is called the **passive** approach to IRNDE, because the heat flow necessary for the evaluation already exists. There are numerous instances where existing transient thermal conditions are exploited in order to use thermography to reveal material or structural characteristics in test articles. The thermogram of the outside surface of an insulated vessel carrying heated liquid, for example, should be relatively isothermal and somewhat warmer than the ambient air. Insulation voids or defects will cause warm anomalies to appear on the thermogram, allowing the thermographer to pinpoint areas of defective or damaged insulation.

Here a passive approach can be taken because the transient heat flow from the liquid through the insulation to the outside air produces the desired characteristic thermal pattern on the product surface. Similarly, water-saturated areas on flat roofs will retain solar heat well into the night; long after the dry sections have radiated their stored heat to the cold night sky, the saturated sections will continue to radiate and exhibit distinct anomalies to the thermographer.

When there is no heat flow through the material or the test article to be evaluated, an **active**, or "**thermal injection**" approach is used to generate heat flow. **Active thermography**, as it has come to be called, is based on the fact that a good structural bond is also a good thermal bond. As is often the case when the samples or materials to be evaluated are already finished products, they are at ambient temperature and there is no heat flowing in or through them. It is then necessary to generate a controlled flow of thermal energy through the structure in a manner that relates the integrity of the sample to the temperature distribution at one or more of the sample's surfaces. Chapter 5 contains more detailed discussions of active thermography techniques and of the equipment and performance parameters necessary for performing active thermography. Chapter 6 contains a review of the current practices of active thermography and some successful case histories.

3

INFRARED THERMOGRAPHY FOR TRANSMISSION AND DISTRIBUTION AND SUBSTATION APPLICATION

Infrared thermography (IR) has demonstrated its usefulness in a multitude of electrical and mechanical inspection applications throughout the power station. Readily available IR imaging systems and image analysis software packages have facilitated implementation of IR for a variety of utility applications. As a key predictive maintenance tool, IR has contributed to cost savings and improved plant performance through elimination of unnecessary preventive maintenance tasks and identification of operational anomalies that could potentially affect plant availability. IR is also a useful diagnostic tool for troubleshooting of mechanical and electrical systems and for identification of air in-leakage on negative pressure systems.

The EPRI *Infrared Thermography Guide, Revision 2* (NP-6973s, Rev. 2) lists typical applications that include electrical connections, switchyard disconnects, transformers, motor control centers, valves, bearings and couplings. In addition to these on-site plant applications, IR is also used for high voltage transmission and distribution line (T&D) systems and substation inspection applications. The recent trend toward operating these facilities at higher than normal load capacities requires that these systems be well maintained and periodically inspected to ensure system integrity and availability.

Many potential problems in these systems result from elevated electrical resistance due to loose or corroded connections, broken conductor strands, dirty contact surfaces or otherwise degenerated components such as cracked insulators. The elevated resistance associated with these problems manifests itself as heat, creating a localized heating event or thermal anomaly that is detectable using IR equipment.

The heat dissipation associated with the thermal anomaly can be characterized as energy lost to heat generation creating a system inefficiency. The rate of heat generation can be expressed as the product of the resistance (voltage drop) in the component and the square of the current. As resistance increases, heat generation increases, elevating temperature in the immediate vicinity of the problem [2]. Long term effects of this uncorrected condition can be translated to lost revenue as a direct result of system inefficiencies. This condition also contributes to accelerated component performance

degradation and, ultimately, component failure that can adversely affect the entire system [3].

Timely detection of potential problems on high voltage systems help to ensure system integrity, minimize down time, maintain revenues and ensure customer confidence and satisfaction [4]. Infrared thermography has become a key inspection technology for assessment of the operating integrity of transmission and distribution systems, substations, and plant switchyards. A variety of IR inspection equipment is currently being used for these applications.

3.1 Utility Survey

The EPRI NDE Center surveyed utility thermographers involved with inspection of transmission and distribution systems, substations and plant switchyards to establish current industry practices. A variety of subjects were covered in the survey questionnaire in an attempt to establish an industry benchmark. Results from the survey are included in this document to provide an insight to the current state of the art.

3.2 IR Equipment

IR systems currently in use by the survey respondents included a wide variety of inspection technology, similar to the selection of equipment used in other utility predictive maintenance applications. The list of respondents' equipment included pyrovidicons, short wave, long wave, and broadband imagers, focal plane arrays, and airborne FLIR units. Selection of IR equipment is based upon a variety of performance, cost, and availability considerations as well as individual operator preferences. Ultimately, selection of the IR equipment should be matched to the requirements of the inspection application.

A working knowledge of the IR system performance characteristics is essential for successful inspection applications. Characteristics such as minimum resolvable temperature, spatial resolution, and spectral response are some of the defining equipment performance parameters that establish the limits of information that can be derived from the target of interest [3]. A detailed explanation of performance parameters for IR equipment is presented in Chapter 1 of the EPRI *Infrared Thermography Guide, Revision 2*, (NP-6973s-Rev. 2). The use of wide-angle, close-up, or telescopic lenses, or, special filters will also affect the system operating characteristics. Each of these performance considerations is generally addressed by the equipment manufacturer in the users manual. The thermographer must be able to apply this knowledge to the inspection application.

IR equipment used by the respondents to the survey included Agema 470, Inframetrics 740 and 760, and ISI Video Therm 94.

3.3 Target Considerations

Use of infrared thermography for inspection of electrical equipment implies that qualitative (non-measuring) or quantitative (measuring) temperature information will be determined from the target component. In a qualitative examination, the IR operator identifies components requiring maintenance or further evaluation based upon recognized anomalies in the thermal image. In many applications, qualitative inspection is sufficient for identification of defective components. This is especially true in situations where any deviation in thermal performance between components in close proximity or components performing the same function is reason for further investigation. Qualitative IR can also be implemented for situations where distance to target, relative target motion, or other mitigating conditions are not conducive to quantitative measurements.

Quantitative examination is also based upon operator recognition of anomalies in the thermal image but includes additional information in the form of an absolute or delta temperature measurement. Absolute temperature measurement requires the thermographer be completely familiar with the temperature measurement capabilities of the IR system (performance parameters such as temperature range, spatial resolution, spectral range) and account for target characteristics such as emissivity, orientation, distance to target, atmospheric attenuation, and reflected energy. The thermographer must also consider the equipment loading at the time of inspection, and, especially in the case of outdoor inspections, the effects of environmental conditions, for evaluation of identified anomalies.

The delta temperature method, or ΔT, is a simpler and faster means of documenting problem conditions. Consequently, the ΔT method is the more popular for assessing electrical equipment problems. Implementation of the ΔT method requires determination of a reference for comparison. For electrical inspections, a similar component operating under similar load can be used as a reference. An example would be an adjacent phase of a three phase system. It is reasonable to expect that each phase should be operating under similar load conditions and any significant ΔT between phases is indication of a problem. This holds true also for evaluation of conductors and connections. Assuming that a good connection should have no more electrical resistance than the conductor, it would be expected that thermal anomalies would indicate a loose, dirty or corroded connection. ΔT measurements can also be referenced to ambient temperature. This provides a common reference measurement point for all electrical components in a given system [5].

3.4 Equipment Transport

Deployment of IR equipment to the field for assessment of transmission, distribution, and substation components can be accomplished in several ways. The survey results indicated that transmission line inspections are typically done airborne. (Exceptions to this included surveys conducted on foot, horseback, or with 4-wheel drive vehicles.) Rotary or fixed wing aircraft are used with a variety of IR system configurations that include commercially available systems, as well as adaptations of hand-held or cart-mounted systems. Commercially available gimbal-mounted imagers, with remote control and monitoring, are available from several vendors. These units mount externally on the aircraft (usually underneath) to provide maximum imager movement with minimal obstruction for viewing. Hand-held IR cameras are also used by utilities in airborne applications. For this adaptation, the camera is generally mounted inside the aircraft and is controlled directly or remotely by the operator. This configuration requires removal of an aircraft door to allow an unobstructed view for the imager. Hand-held IR imagers have also been mounted externally on aircraft in a fixture that allows remote control of the camera and positioner by the operator. This eliminates the need for removal of a door and provides increased comfort for the operator, pilot, and spotter.

To a limited extent, distribution lines and substations are also inspected using airborne equipment. In most cases, this is a redundant examination with the primary inspection being conducted from the ground. The survey respondents indicated that distribution systems are primarily assessed with truck or van-mounted equipment. Dedicated vehicles provide IR system portability and a mobile office for data analysis and report writing. Truck and van installations are similar to airborne applications in the variety of fixtures used for mounting the imager. These range from simple imager fixtures that hang on the passenger door glass to other more permanent installations such as roof-mounted video cameras and IR imagers that can be controlled remotely from inside the vehicle or manually through a port in the roof. Some utilities also use these vehicles for substation inspection, where convenient.

Many of the survey respondents rely primarily on cart-mounted or man-portable systems for inspection of substations, allowing maximum mobility for the thermographer.

3.5 Auxiliary Equipment

Auxiliary support equipment for IR includes a variety of technologies that aid data acquisition, recording, and report writing. Complementary inspection technologies are also employed to more thoroughly investigate suspect components.

Standard visible light cameras, video cameras, and digital image storage cameras are used to record a visible light image of the component being inspected. Visible light images included in an IR inspection report serve to identify a component for engineering analysis, subsequent maintenance activities, management review and post-repair inspections. (High resolution focal plane array IR equipment provides an excellent quality, readily recognizable thermal image and might preclude the need for a visible light image in some applications.) Digital cameras offer the advantage of high quality images that can be imported directly into many report generation software packages. Video recorders are used to document visible light and IR images of suspect components or to record an entire inspection sequence, as in the case of airborne inspections. Video images can then be captured using a combination of frame-grabber board and software for inclusion of the video image in a report format.

As mentioned previously, a variety of commercially available and custom-built fixtures and positioners have been incorporated for improved IR inspections. Additionally, airborne inspections might incorporate gyrostabilizer units for video camera and IR imagery stability. For improved anomaly location identification, global positioning system information can be integrated with IR images to provide precise location coordinates for subsequent repair or reinspection activities.

Complementary inspection technologies such as vibration and oil analysis, ultrasound, and night vision equipment are also used in support of IR.

3.6 Personnel Training Requirements

The survey of utility thermographers indicated that personnel training requirements are specified procedurally by each utility. Training requirements for personnel performing IR inspections generally followed the recommended training identified in the American Society for Nondestructive Testing (ASNT) document SNT-TC-1A for Level I and Level II thermographers. Most IR personnel received formal Level I and Level II training from EPRI or other commercial training companies, that follows the general guidelines of the SNT-TC-1A document. Additional specific training for inspection of transmission and distribution systems and substations is provided as on-the-job training by competent utility or consultant personnel. IR system training is available from the equipment manufacturer or other knowledgeable personnel.

3.7 Inspection Parameters

As with inspection of transmission and distribution systems, a variety of inspection parameters must be considered to facilitate a meaningful evaluation. The system or component being evaluated must be operating. Most thermographers polled preferred that the system or component be operating at 50% of rated load to provide meaningful inspection information. The thermographer should also be aware that anomalies

identified at partial load will become more severe as the component approaches maximum loading.

This relationship can be illustrated using the formula $P=I^2R$, where "P" represents the circuit power in watts, "I" represents electrical current, and "R" represents resistance. Thermal anomalies in electrical circuits are generally points of resistance in the circuit. As circuit load (I) increases, the power dissipated across the resistive load increases. In the case of loose or corroded connections, broken conductor strands, or a bad splice, dissipated power increases with the square of the circuit load (I), resulting in severe degradation or failure of the anomalous component.

This load information can be included in the thermographer's report to provide additional data for scheduling of maintenance action. Conversely, components scheduled for inspection that are out-of-service during the inspection interval, should be duly noted. This avoids assumptions being made about component suitability for service based on no anomalies identified for the component.

Emittance characteristics of the component being inspected are an important consideration since they can adversely affect apparent temperature information. Low emittance targets, in general, are highly reflective. Solar reflections or reflected energy from adjacent components (including the thermographer) can deleteriously affect inspection of low emissivity components. Coatings, such as flat paint or liquid penetrant developer, can be effective in improving emissivity of reflective components, but are not always procedurally acceptable or practical to apply. In the case of solar reflections, repositioning of the IR camera will result in relative movement of the thermal anomaly indicating the presence of a solar reflection. IR systems operating in the short wave (3-5μm) range are more susceptible to solar reflections than long wave (8-12μm) equipment. Suspected reflections from adjacent equipment can be identified by screening the suspect component (with a clipboard or piece of cardboard) where practical, or repositioning the IR camera and observing the behavior of the thermal anomaly.

Ambient conditions such as temperature, wind velocity, solar loading, and atmospheric attenuation can also have a dramatic effect on the apparent temperature of a target. Inspection of outdoor installations can be influenced by any one or a combination of these factors. A minor anomaly detected in cold ambient temperature conditions might manifest itself as a severe problem when ambient temperatures become warmer. Windy conditions might also mask or minimize problem areas. In the daytime, as wind speed increases, the cooling effect increases exponentially, indicating that calm wind conditions are necessary for effective inspections [5]. Conversely, solar loading effectively increases the temperature of the component of interest as well as the surrounding support structure and associated equipment. Inspections done early in the morning or on overcast days will experience minimal effects from solar loading.

Atmospheric attenuation is also a factor when inspecting components over relatively long distances. Dust particles, moisture, and carbon dioxide will attenuate infrared energy over distance inhibiting thermal measurement and target recognition. This phenomenon is more pronounced when using short wave IR equipment to observe a relatively cool target through a long atmospheric path. Temperature / distance compensation algorithms, such as LOWTRAN (developed by the U.S. Air Force Geophysics Laboratory) can be used with an IR system's atmospheric attenuation function to compensate for the attenuation of radiation emitted from the target due to scattering or absorption by the atmosphere. This process can be useful for correction of target temperature when quantitative measurements are required [6].

Prior knowledge of a component's "normal" thermal profile is advantageous and can save significant time when identifying anomalies. Assistance from engineering and craft personnel familiar with component operating characteristics and normal failure modes can be invaluable when evaluating thermal anomalies of operating equipment.

3.7.1 Acceptance Criteria

The EPRI *Infrared Thermography Guide, Revision 2* (NP-6973s-Rev. 2) includes an acceptance criteria with four levels of criticality. The levels were derived from survey results provided by utility thermographers. The four levels are:

Advisory	1 to 15°F rise above a reference (0.5°C – 8°C)
Intermediate	16 to 50°F rise above a reference (9°C – 28°C)
Serious	51 to 100°F rise above a reference (29°C – 56°C)
Critical	in excess of 100°F rise above a reference (56°C)

The **reference** level, identified in the acceptance criteria, could be based on ambient temperature or some other identifiable temperature standard (such as an adjacent phase in a three-phase electrical circuit). In practice, no singular acceptance criteria is universally applicable to the variety of components a utility thermographer is called upon to inspect. Consequently, acceptance criteria must be developed for each category of equipment based upon its operating characteristics, failure modes, and critical importance to operations.

3.8 Candidate Components

A variety of substation, transmission, and distribution components are good candidates for inspection with infrared thermography. Components inspected with IR include stand-off insulators, lightning arrestors, potential transformers, coupling capacitors,

current transformers, load tap changers, circuit breakers, disconnects, bus, bolted connections, ground connections, bushing connections, and line splices.

3.9 Report Writing

Commercially available IR analysis and report writing software packages fulfill the reporting criteria for a majority of utility thermographers. Software is available from the major equipment manufacturers and several independent sources. These software packages allow customization of the report forms to meet the thermographers' needs and provide a convenient platform for importation of IR and visible light images, descriptive text, spreadsheet data, and other pertinent information. The resulting report is professional in appearance and informative in content.

Regardless of the report format, several reporting requirements must be met to effectively document the infrared inspection. Chapter 6 of the EPRI *Infrared Thermography Guide, Revision 2* (NP-6973s-Rev.2), lists the following criteria required for an effective report form:

- Time / date
- Equipment identification
- Location
- Specific problem
- Corrective action
- Visible light image
- Infrared image
- Inspector's name and signature

Additional specific information related to component temperature vs. acceptance criteria, ambient temperature conditions, equipment load (for electrical equipment), and IR camera and lens identification is useful for subsequent data analysis and re-inspection.

3.10 Safety Considerations

IR inspections of electrical equipment require strict adherence to company safety procedures and appropriate OSHA regulations. Removal of electrical panels to facilitate inspection or working in close proximity to high voltage equipment exposes the thermographer to potentially injurious or life threatening situations. Assistance from

knowledgeable electrical personnel can greatly reduce risk of injury and help to avoid interruption of service during an inspection of electrical equipment. The National Fire Protection Association document NFPA70E, is a valuable reference for determining appropriate personal protective wear and safe working distances for high voltage inspections.

Airborne inspections require additional safety considerations regarding safe operation of the aircraft and crew safety. Planning prior to an airborne inspection should include a review of the course to be flown, flight speed, distance to target (especially proximity to high voltage lines), identification of obstacles, target / component identification, plans for refueling, and considerations for crew fatigue. In addition to pilot and thermographer, a spotter is essential for safe operation of the aircraft for airborne inspection.

4

REPRESENTATIVE THERMAL IMAGES FOR TRANSMISSION AND DISTRIBUTION AND SUBSTATION COMPONENTS

Infrared surveys of T&D and substation components can identify operational problems well in advance of component failure. This capability is a major contributor to overall system efficiency and reliability. This chapter contains several thermal images of representative components (Figures 4-1 to 4-7).



Figure 4-1
Connection to Bus in Substation
(courtesy of R. Miner, Thermal Techniques)



Figure 4-2
Transformer Bushing
(courtesy of R. Miner, Thermal Techniques)

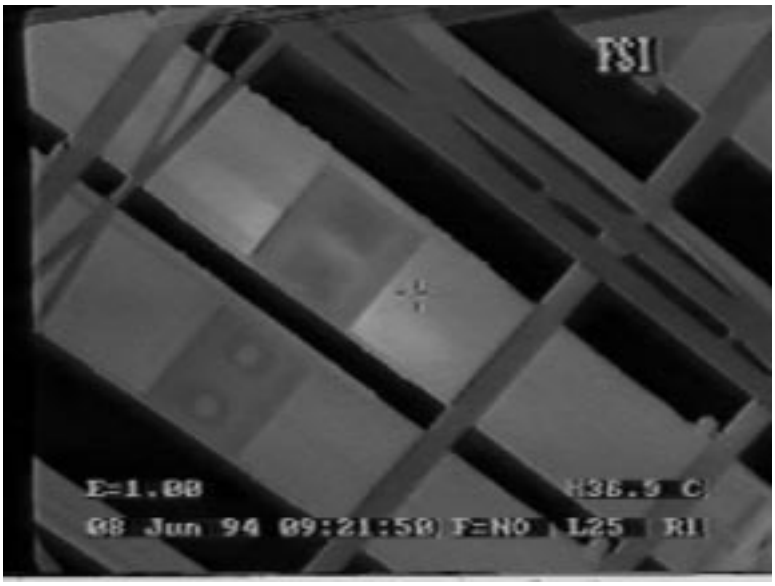


Figure 4-3
Bus Bar Joint Connection
(courtesy of R. Miner, Thermal Techniques)

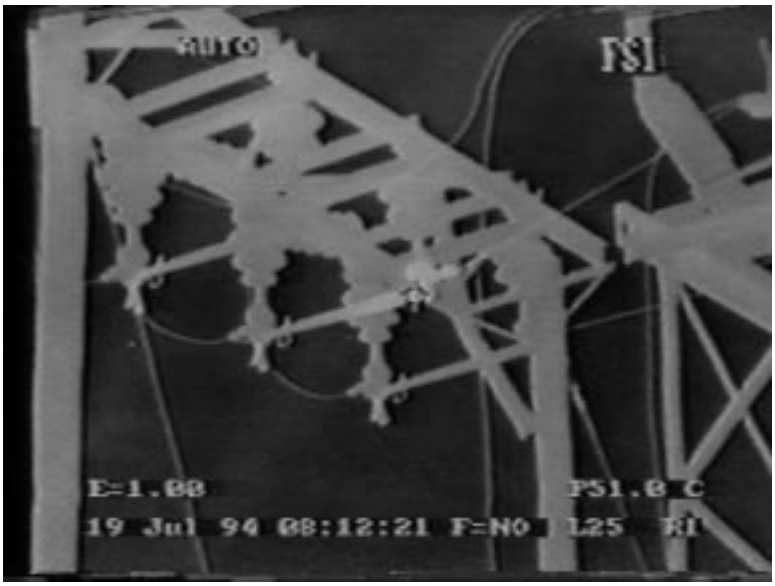


Figure 4-4
Substation Knife Switch
(courtesy of R. Miner, Thermal Techniques)

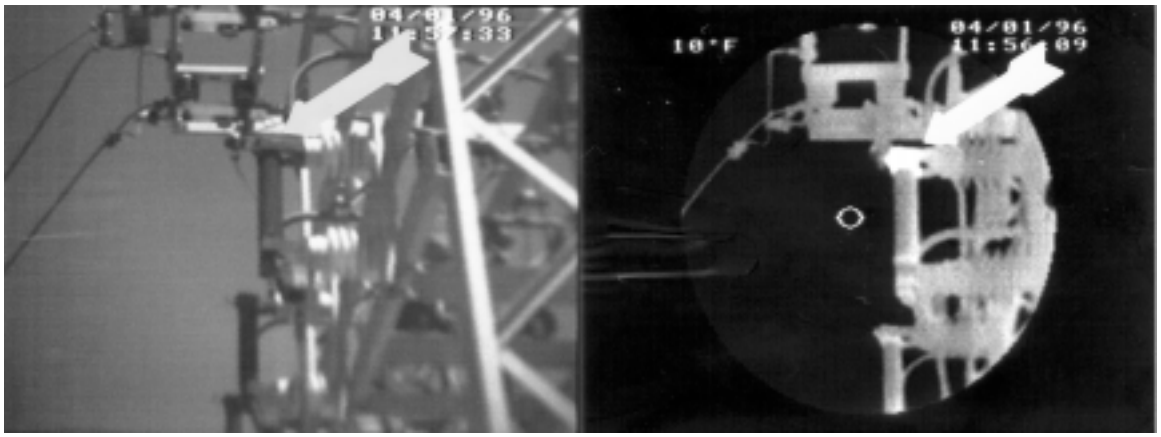


Figure 4-5
Low Side Cutouts. Visible Image (left) and Thermal Image (right)
(courtesy of D. Comes, Oklahoma Gas & Electric Co.)

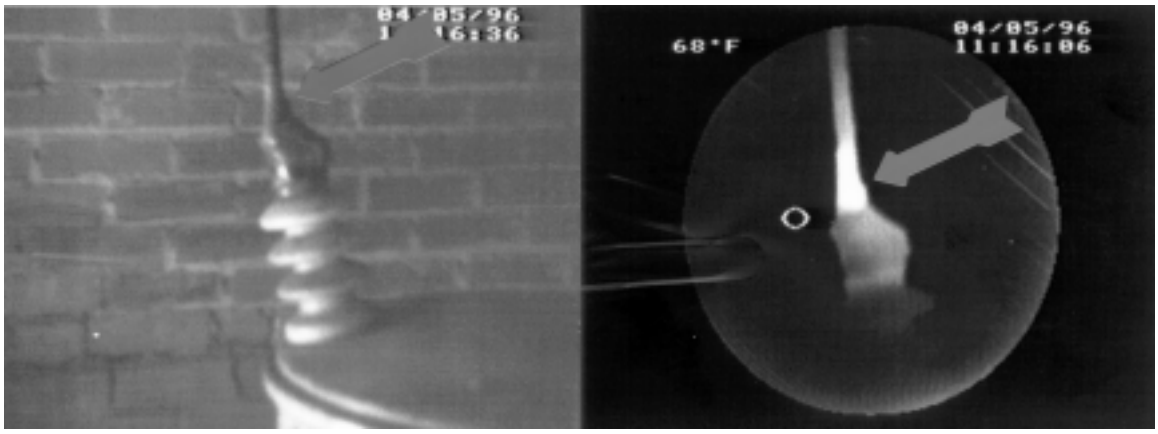


Figure 4-6
Walk-In Vault, Primary Bushing. Visible Image (left) and Thermal Image (right) (courtesy of D. Comes, Oklahoma Gas & Electric Co.)

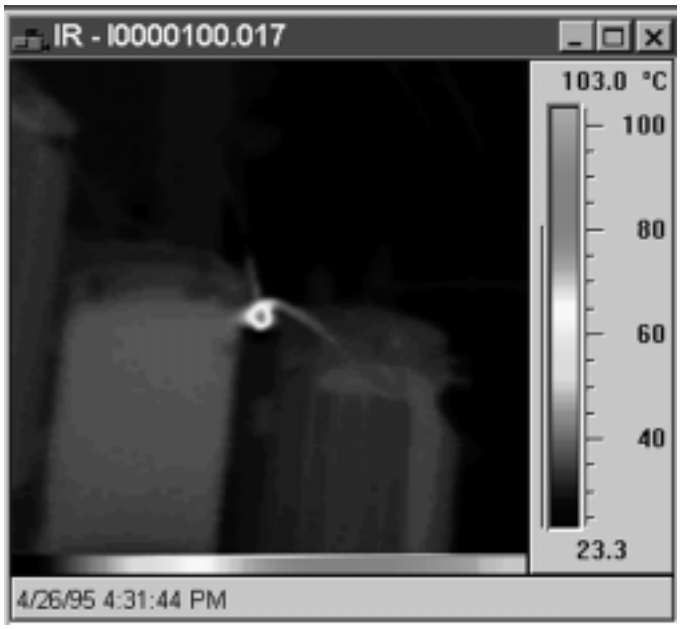


Figure 4-7
Transformer Connection in Distribution System (courtesy of J. Davis, TU Electric)

5

ACTIVE IR THERMOGRAPHY TECHNIQUES

5.1 Introduction to Active Thermography

When IR thermography is to be used to evaluate materials or components that are thermally static (all points are at ambient temperature), it is necessary to generate a flow of thermal energy such that the structural properties of the material or sample can be made to enhance or impede this flow. When this is done effectively, thermograms of the test samples will indicate variations in these structural properties. **Active IR thermography** involves the introduction of a systematic and controlled amount of heat to the sample under test, thermographic monitoring of one (or more) of the surfaces of the sample, and the search for the anomalies in the thermal patterns, so produced, that will indicate a "defect" in accordance with established accept/reject criteria. This approach has been used extensively and successfully for many years by the aerospace community in the evaluation of composite structures for impurities, flaws, voids, unbonds, delaminations and variations in structural integrity. Figure 5-1 illustrates a typical active thermography configuration, where voids, unbond, and occlusions in a laminated sample are detected by applying uniform heat to one surface and monitoring the thermal image of the opposite surface.

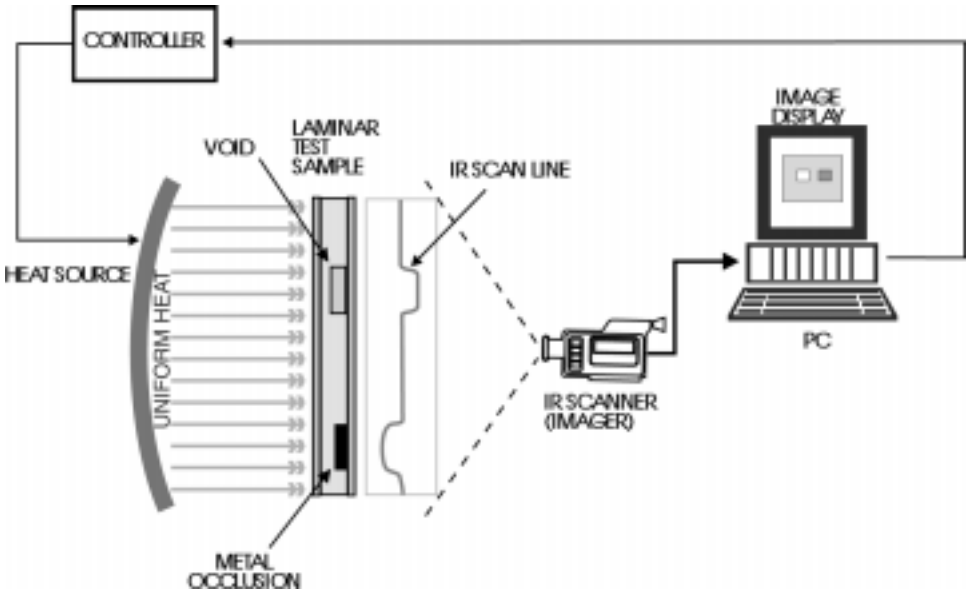


Figure 5-1
Example of Active (Heat Injection) IRNDT for Occlusion and Void Detection

Because the voids and delaminations have poorer thermal conductivity than the laminate material, they impede the flow of heat and the monitored surface will appear cooler over voids and delaminations. Because a metal occlusion has a higher thermal conductivity than the laminate material, it enhances the flow of heat and the monitored surface will appear warmer over the metal occlusion. The illustration also shows the injection of heat under operator control by means of the computer keyboard. Here the computer's diagnostic software can perform image processing functions and control the flow of heat through the test sample if required. This level of sophistication in control is not necessary in the vast majority of current material testing applications but currently available equipment and software are equal to the task.

In the example of Figure 5-1, the success of the test application depends on many factors, most of which are under the control of the thermographer and will be discussed later in this chapter. This application is typical of most material testing applications and does **not** depend on temperature measurement—since the thermal flow is under user control, the absolute value of the surface temperature is of little importance and **qualitative thermography** can be used. There are other performance parameters of the imager that are critical to the success of the application, however, and these will also be discussed in this chapter.

5.2 Variables Determined by the Thermographer

The equipment necessary to perform active thermography must include not only thermographic scanning instrumentation, but also the means to handle the test samples

and to generate and control the injection or extraction of thermal energy to or from the samples. In any active thermography application, the control of the test method rests on the thermographer, who must plan the program and determine the test accept / reject criteria for each test article. Virtually all of the following variables are selected or controlled by the thermographer:

- Test location and environment
- Test sample mounting and fixturing
- Type of heat injection or extraction (or both)
- Point of application
- Amplitude of heat injected or extracted
- Rate, duration, and frequency of heat injection or extraction
- Treatment of test sample surface(s)
- Selection of thermal imager
- Selection of ancillary equipment
- Timing of thermographic scanning
- Type of recording and record keeping

The factors that are ***not*** under the control of the thermographer are those that concern the characteristics and configuration of the planned test articles. These include:

- Size and shape of the test article
- Thermal properties of the materials
- Ruggedness of the samples
- What is an acceptable test sample?
- What is an unacceptable test sample?

5.2.1 Test Location and Environment

Except for situations where in-situ testing is required or where test samples are large and heavy, most test samples can be brought to a selected test location. In general, a test area should be selected that is environmentally mild and stable. The air temperature should be controlled. The area should be free from, or protected from, extraneous sources of heat that include winds, convection currents, and IR thermal

radiation such as those from lighting fixtures (particularly incandescent lamps, but fluorescent light ballasts can also be a source of difficulty) and heating equipment.

The location should be chosen such that the test background (what will appear in the thermogram behind the test sample) is isothermal and of uniformly high emissivity. The instrument background (what will be behind the imager and might be reflected into the thermogram from low emissivity surfaces on the target) should be chosen similarly. A simple matte screen partition placed behind the imager during dry runs and actual testing might serve this purpose adequately.

In anticipation of future requirements, the test area should have or be near, a source of running hot and cold water, a water drain, a supply of compressed air, and electrical power outlets adequate to operate heat injection equipment as well as thermal imaging equipment.

5.2.2 Test Sample Mounting and Fixturing

Depending on the requirements, fixtures to hold and manipulate the test samples can range anywhere from simple clamps and vises, to complex, remotely-controlled multi-dimensional positioning mechanisms.

5.2.3 Mechanisms for Heat Injection or Extraction

Heat injection and extraction mechanisms available for active thermography include hot and cold air blowers, liquid immersion baths, radiant heat lamps, flash lamps, controlled refrigerants, electric current, pulsed and scanned lasers, and induction heating. It might sometimes be useful to inject heat into one location on a test sample and extract it from another location (blow hot air on one surface of a laminate and cold air on the opposite surface). The heat flow can be **continuous** or **pulsed**. In the sample application shown in Figure 5-1, the applied heat is **continuous**—the heat flow is maintained at the same rate throughout the test. The goals in this type of test are to optimize the flow through the material (usually normal to the surface), minimize the lateral thermal flow (along the material surface), and generate as uniform a thermal pattern as possible across the surface of the test sample. Since the source of energy is finite in dimension, the generation of a uniform thermal pattern on the sample surface might be difficult to accomplish. In **pulsed** heat injection, the methods and goals are somewhat different. Here, the energy is switched on and off for predetermined durations and at predetermined intervals and the observation of transient phenomena is usually more significant than in the **continuous** heat mode. Pulsed heating techniques will be discussed in greater detail later in this chapter.

An important consideration is, whatever the selected mechanism, the injection or extraction of heat must be nondestructive—it should cause no permanent damage to the test samples.

5.2.4 Treatment of Test Sample Surfaces

For most active thermography applications, the ideal surface to be monitored (at which the imager is aimed) is one that is high and uniform in emissivity. This is because surface anomalies such as scratches and other emissivity non-uniformities will cause apparent temperature variations unrelated to the defects that need to be detected. These artifacts can be prevented, when testing conditions permit it, by the application of a high emissivity coating to the measurement surface. An important consideration here is that the coating must be able to withstand the temperatures involved in the test without blistering or degrading. Another consideration is that the coating must be readily removable by the use of non-toxic solvents. There are high emissivity, high temperature coatings available for this purpose. For low temperature applications, the choices are far more numerous and include the application of electrician's tape, stretch plastic film, and foot powder. The *actual value* of the effective emissivity of the coating is of less importance in active thermography than it is in temperature measurement applications because, in most active thermography applications, temperature measurement is not necessary.

When surface treatment is not permitted, the thermographer has access to numerous image manipulation software routines including keyboard-controlled real-time image subtraction. The image subtraction capability can be quite effective in compensating for emissivity variations. Here, the displayed image is subtracted from itself just prior to the application of heat. The resultant "difference" image is initially free of emissivity artifacts and the effect of surface emissivity variations on the subsequent test run will be substantially minimized.

5.2.5 Pulsed Thermal Injection Techniques

Since as early as 1970, active thermography has been applied to the detection of flaws in aircraft structures and most major airframe manufacturers have ongoing in-house programs. An important recent innovation to heat injection techniques has improved its effectiveness in existing applications and widened the potential range of applications to include materials whose thermal characteristics had previously excluded them from this approach. Recently, test samples, such as steel pipes with relatively thick sections, have been successfully inspected and considerable promise is seen for future in-situ evaluation. This is of significance to thermographers operating within a plant or facilities environment where inspection of steam and water piping for erosion, corrosion, and wall thinning is most desirable.

Pulsed Thermal Injection is a general term used to describe a technique with many variations. Most of these involve the introduction of high-intensity short-duration thermal pulses to one surface of a test article and the high speed monitoring of this same surface, resulting in improved capabilities for detecting small and buried flaws. The availability of high speed infrared focal plane array imagers and improvements in computer enhancement methods for isolating and analyzing thermographic patterns, have had a profound effect on the ability to recognize and evaluate flaws and failure mechanisms using pulsed thermal injection techniques.

In one of its forms, pulsed thermal injection is popularly referred to as **thermal wave imaging** because the thermal flow within the test sample is similar to that of a wave of energy propagated into the surface and echoing off thermal discontinuities. The "**thermal wave**" technique is illustrated in Figure 5-2. The target surface is irradiated with short duration pulses of thermal energy using high intensity sources such as xenon flash lamps. Between pulses, as the surface cools, the heat front is conducted into the material at a uniform rate until it reaches a thermal barrier or discontinuity, such as a flaw. A portion of the heat is conducted back to the surface which, at this time, is cooler than the flaw site. The time it takes from the generation of the pulse to the reheating at the surface is an indication of the depth of the flaw. Computer software can be used, when necessary, to correct for the non-uniformities in the effective temperature pattern of the lamps, and to regulate pulse timing, intensity, and duration. Software is also available that facilitates the precision timing and recording of test sequences so that they can be repeated with consistency.

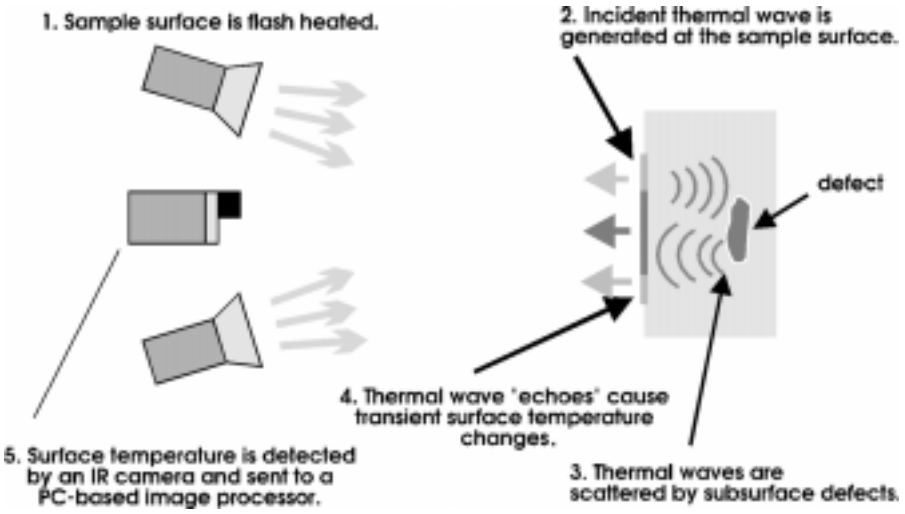


Figure 5-2
Conceptual Sketch of Thermal Wave Imaging
(courtesy of Thermal Wave Imaging, Inc.)

Several approaches are used to process the resultant images. **Time gating** is one of these approaches. Time gating is accomplished using processing software that allows

the thermographer to "search" through sequential stored images. The effect of time gating can be seen by comparing the thermal contrast pulses illustrated in Figure 5-3. The initial injection pulse is shown at the left.

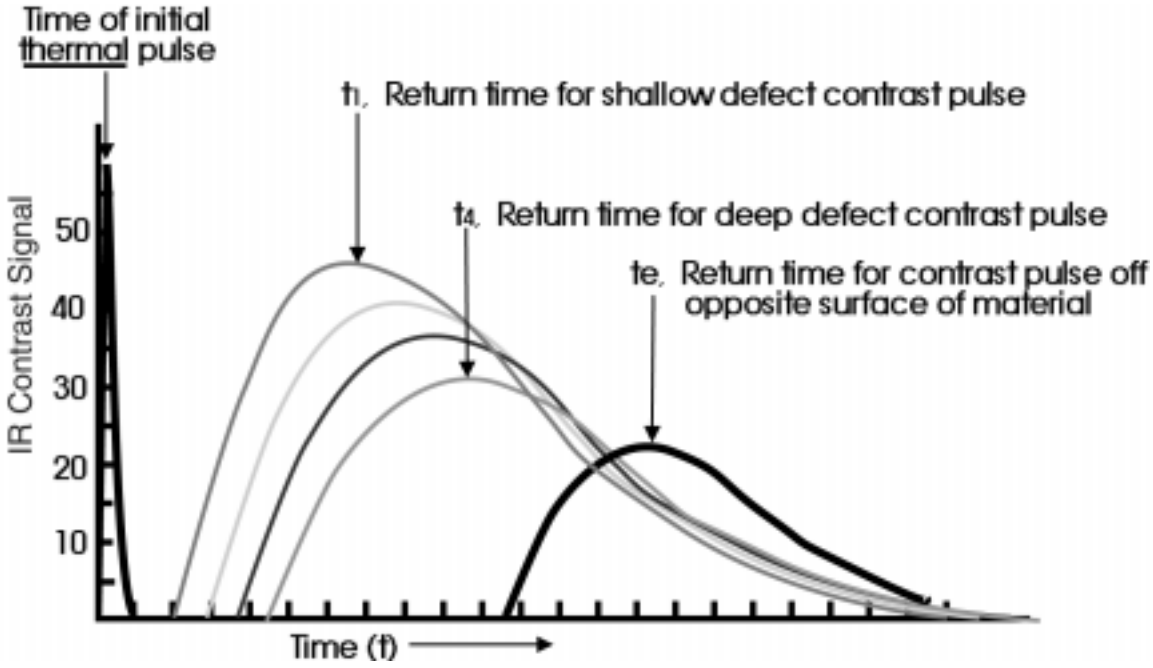


Figure 5-3
Time/Contrast Profiles for Pulsed Thermal Injection

All other factors being equal, the timing of the subsequent reheating of the surface can then be related to the depth of the thermal discontinuities encountered—the reheating energy from a shallow defect will reach its peak sooner and that from a deeper defect will peak later. Consequently, a time-dependent image search can yield the optimum image of flaws at any given depth.

5.2.6 Heat Flow Properties Of Materials

In order to optimize active thermography results on a particular sample, the heat flow characteristics of the material must be known. While radiation properties of a material (emissivity, etc.) are important for imaging purposes, a knowledge of its conductive properties, particularly **thermal diffusivity**, are critical to the choice of heat injection parameters (type, amplitude, duration, frequency, and so on). Thermal diffusivity is a measure of how quickly a material can change its temperature; it takes into account its mass density, thermal conductivity, and specific heat. It is very high for metals such as copper and aluminum, not quite as high for metals such as steel and nickel, and low for glass, plastics, fibers, and epoxy.

Emissivity tables are available from many sources including Chapters 3 and 4 of the EPRI *Infrared Thermography Guide, Revision 2* (NP-6973s-Rev. 2). A table of conductive properties (such as thermal diffusivity) of various common materials can be found in *Maldague, Nondestructive Evaluation of Materials by Infrared Thermography, Table 1.1* [7]. Section 1.2.2 of this reference features an in-depth discussion of the mathematics involved in time gating. There is also a discussion in Section 5.2 which relates IR nondestructive evaluation of corrosion damage to pipes to the thermal properties of the pipe materials.

The heat transfer characteristics of the materials being investigated can be critical to the selection of the IR imaging equipment as well as the heat injection source.

5.2.7 Instrument Performance Parameters for Active Thermography

The most significant imager performance parameters for active thermography applications are: **spatial resolution**, **thermal resolution** and **frame rate**. The significance of each of these parameters in a typical active thermography application is discussed in this section. The other performance parameters will also be discussed.

5.2.7.1 Spatial Resolution

As active thermography techniques evolve, so will the capability to detect smaller, deeper and more subtle defects. The spatial resolution of the imager is a measure of how small a defect can be clearly detected. Currently available "top-of-the-line" IRFPA imagers, in general, offer spatial resolution improvements of two to three times over their scanning radiometer counterparts (standard IFOVs of about 1mRad compared to 2 to 3mRad). An IFOV of 1mRad (1 milliradian) means that the instrument can image a 1mm anomaly on the target surface at a working distance of 1 meter, a 10mm anomaly at 10 meters, and so on. Fortunately, most of the new instruments coming on the market are based on IRFPAs and the inherent improvement in spatial resolution will keep pace to some extent with the challenges of many new active thermography applications.

5.2.7.2 Thermal Resolution

Thermal resolution is a measure of how small an effective temperature difference (blackbody equivalent) on the target surface can be detected by the instrument. Most currently available thermal imagers are capable of detecting an effective difference of 0.1 to 0.2°C for steady state measurements. This is currently more than adequate for most active thermography applications since the user can control the amount of heat applied. For high speed measurement of transient phenomena, however, thermal resolution for a given imager begins to degrade. The degradation is more rapid for a

scanning imager than it is for an IRFPA imager since each detector element of the IRFPA imager is staring at an assigned IFOV on the target surface while a scanning imager detector must scan the entire target surface every frame. As active thermography requirements for transient thermal measurements proliferate, the thermal resolution benefits offered by IRFPA imagers will make them more desirable for these applications.

5.2.7.3 Frame Rate

The frame rate is the image repetition rate, a measure of how frequently the thermal imager reports the measurement at each pixel. For currently available scanning imagers, this ranges from 10 to 60 frames per second (fps) and is usually limited by the speed of response of the detector since the detector, usually a single element, must scan every target pixel. For most current active thermography applications, a 30fps frame rate is more than adequate. As more transient measurements are required, however, the capacity of IRFPA imagers to respond more rapidly will make them more desirable for some applications. Since most cooled FPA detectors have intrinsic time constants on the order of microseconds, the limiting factors in frame rate are in the instrument's electronics rather than the detector. Image repetition rates of 1KHz are currently available with some cooled FPA imagers.

5.2.7.4 Spectral Region

Currently all commercial IR thermal imagers operate in one of the two atmospheric "windows", in either the 2-5µm or the 8-12µm spectral region, depending upon the spectral sensitivity range of the detector used. Active thermography applications, in general, work equally well in both regions. The exceptions to this occur when the sources or the materials involved have spectral characteristics that would favor one region over the other. One example would be where a 10.6µm laser source is to be used to inject heat into a surface to be monitored by an imager. It would probably be advantageous, in this instance, to use an imager operating in the 3-5µm region, so as to be unaffected by reflected laser energy. Another example would be where the material being evaluated (glass, for instance) is partly transparent to IR energy in the 3-5µm region. Here, it would probably be advisable to use an imager operating in the 8-12µm region, so as not to "see" into the glass.

5.2.7.5 Standard Diagnostic Software

Most thermal imagers include on-board diagnostic software. With improved packaging technology in both computers and thermal imaging equipment, there has been a gradual trend toward providing more and more "on-board" software so that more on-site diagnostics can be performed. The capability of applying emissivity

correction in order to quantify results is usually provided and, as previously mentioned, this is not always important to active thermography applications. Other features associated with quantitative measurement, however, can be very useful. These include the color scale or gray scale, spots or crosshairs that can be placed on the image, and the "isotherm" feature that allows the operator to select a temperature "band" or interval on the target surface such that all areas on the target, within that band, then appear enhanced in a predetermined gray shade or color hue. These features can be used to set and adjust acceptability threshold levels (that is, "If it stays blue it's acceptable; if it becomes red, it should be investigated; if it's yellow, it's a defect.").

Image manipulation features such as line profiles, area scans, frequency histograms, and electronic zoom can be useful in enhancing and emphasizing thermal features of a test article, and the 3-D imaging capability can be used to provide an isometric "thermal contour map" of the target for enhanced recognition of thermal anomalies.

Live image comparison (differential thermography) allows the automatic comparison of a live image to a stored image by means of pixel-by-pixel subtraction. For active thermography applications, this can be extremely useful in reducing the effect of surface emissivity artifacts by subtracting an image from itself prior to heat injection. It is also useful to be able to subtract a live image from itself in order to establish a baseline for subsequent time-based thermal transient measurements.

Most currently available IR imagers feature the capability of recording and retrieving images and data in memory, hard disk, diskette, videotape, and, most recently, PCMCIA (Personal Computer Memory / Computer Industry Association) cards. Some on-board means to store images in the field, such as a floppy disk drive or a PCMCIA card is usually provided. Additional off-site software capability includes database management and report preparation software templates.

5.2.7.6 Custom Hardware/Software and Image Processing

Many of the pulsed thermal injection techniques in current use (and reported in Chapter 6) require the use of custom hardware and image processing software. The software is used to enable time gating of the imager output and to provide synchronization of the scan sequence with the introduction of the thermal pulse into the test article. The hardware is required to tie the control of the heat injection source into the system. Some of these custom packages are commercially available for specific IR imagers and it should be possible, in the near future, to purchase a package to match the performance requirements of a specific active thermography application.

5.2.8 Training for Active Thermography

The interaction of the operator with the process can be the key to a successful active thermography investigation. The operator needs to develop a clear understanding of the relationship between the thermal images being produced and the physical mechanisms at work. Proper training will help bring this about.

The ASNT (American Society for Nondestructive Testing) has established training guidelines for infrared thermographers that can be found in their Recommended Practice document No. SNT-TC-1A. These cover three levels of training. To successfully perform active thermography, training and experience equivalent to ASNT Level II is recommended. The training portion includes the development of a basic understanding of heat and heat transfer mechanisms, infrared physics, target, media, and instrument parameters. In addition, a more detailed investigation of materials and material properties is suggested. Further study of heat injection and extraction methods and equipment is also recommended. Finally, hands-on experience with thermography equipment, in general, is essential, and intensive practice with the specific equipment to be used for the testing is recommended.

6

ACTIVE IR THERMOGRAPHY CASE HISTORIES

This chapter contains several examples of actual work that has been accomplished through the use of active thermography. Each case history is a capsule summary rather than a detailed report. References are cited, however, so that additional information on each specific test can be obtained.

Many of the case histories described in this chapter involve the time-gating of thermal image sequences following the application of heat, usually a pulse, in order to characterize defects at various depths below the target surface. As discussed in Chapter 5, the term **time resolved infrared radiometry (TRIR)** is generally used to describe the technique.

The use of various terms to describe the same or similar techniques are found in the example case histories, as well as in the references cited, and might be somewhat confusing to the reader. Much of the work in this area was pioneered by scientists at Wayne State University, Detroit, Michigan, Johns Hopkins University, Baltimore, Maryland, Universite Laval, Quebec, Canada and other institutions. In its earliest applications, in 1978, the pulse injection technique was limited to single point measurement and was called "photoacoustic microscopy" because, although heat does not generally flow in "thermal waves," the flow of heat in the pulsed samples simulated the propagation and reflection of sound waves. The availability of high speed imagers dramatically increased the speed and, hence, the usefulness and popularity of the technique. The pulsed approach to TRIR thermography has been called **thermal wave imaging, pulsed infrared imaging,** and **time-gated thermography** among others.

In general, a typical "thermal wave imaging" system consists of the following elements:

- A pulsed heat source (flash lamps, pulsed laser, time-gated microwave)
- An IR thermal imaging radiometer
- Image processing hardware (electronic switching and gating)
- Image processing software
- A personal computer

6.1 IR Techniques Evaluation for Detection of Wall Thinning of Water Piping - EPRI

In this program, two methods were investigated for the detection of thinning and other defects in service water piping. The tests were supervised by EPRI NDE Center at the Vermont Yankee facility. They were conducted on mock-up samples prepared for the purpose by Vermont Yankee and on actual in-service piping in areas selected by Vermont Yankee. The mock-ups were of Schedule 40 pipe sections, 4", 8", and 12" in diameter with built-in simulated defects ranging from 10% to 70% wall thinning. All piping tested was uninsulated and was painted by Vermont Yankee to provide a high, uniform emissivity. The first of the two methods involved step heating of the pipe sections using resistance heaters in contact with the O.D. of the pipe. The second method involved pulsed heat injection using Xenon flash lamps. The tests were conducted by two different vendors on identical test articles. The step heat injection approach was used by Thermtech Services using a Bales Scientific imager. The pulse heat injection approach was used by Inframetrics using their EchoTherm system, which incorporates two xenon lamps, a pulsing and acquisition interface furnished by Thermal Wave Imaging, and an Inframetrics 760 imager. Both approaches were tested on the mock-up samples; only the ThermTech approach was tested on the in-service piping.

Some of the ThermTech thermograms appeared to indicate thinning on the in-service piping, but correlation with actual thinning will not be determined until the next outage when ultrasonic testing can be performed. Both approaches were able to detect defects in the mock-up samples. ThermTech was able to detect all the defects and Inframetrics was able to detect thinning of 40% and greater. Neither system could view more than 60° of pipe circumference at any one time but the judicious use of front surface mirrors could allow 360° viewing in future tests.

Indications are that either approach, if optimized, can be used to detect thinning in in-service water pipes down to 10%. The strip heaters used by ThermTech were far less costly than the EchoTherm system but required contact with the pipe surface and were more time consuming to apply and remove. The comparative success of the ThermTech approach was, more likely, due to the fact that the Bales imager has a higher spatial resolution than the Inframetrics 760. The use of IR focal plane array imagers for future measurements should improve detectability.

Figure 6-1 is a representative IR image of the Vermont Yankee mock-up using the Inframetrics EchoTherm System.

For more information:

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ThermTech Services	(201) 661-1748	Tom Reilly
Inframetrics	(508) 670-5555	Ed Jones
Thermal Wave Imaging	(810) 569-4960	Steve Shepard

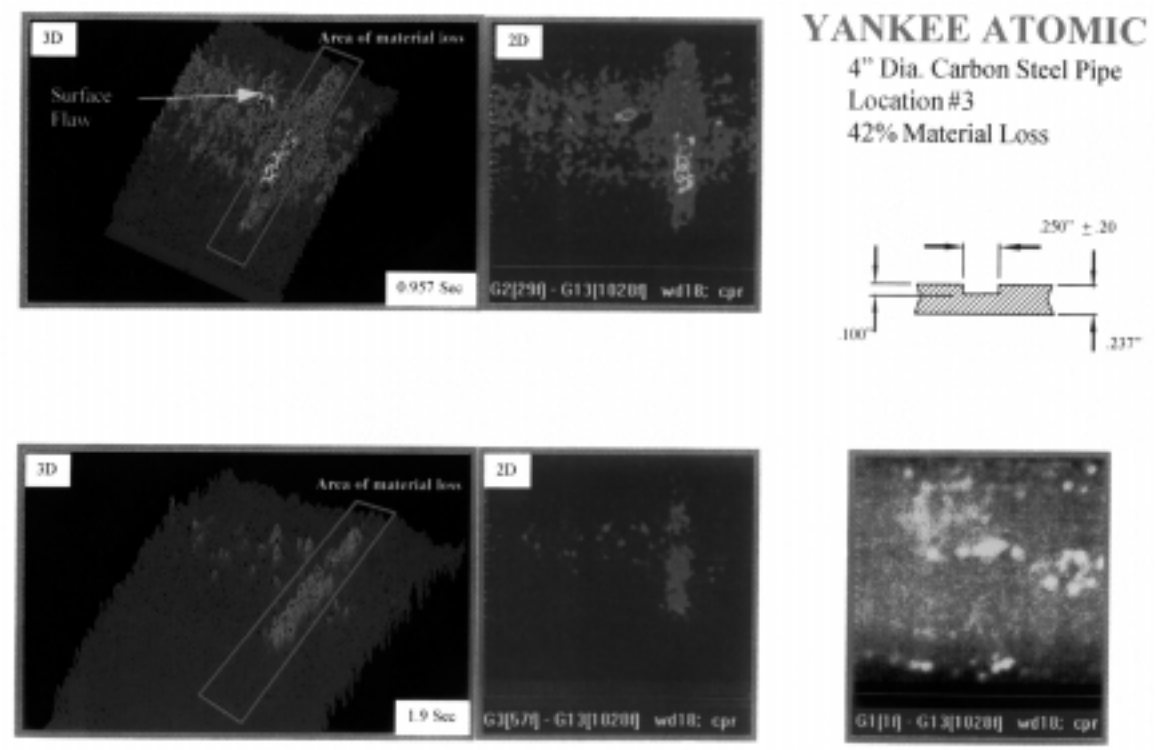


Figure 6-1
IR Image of the Vermont Yankee Mock-up Using the Inframetrics EchoTherm System [8]

6.2 Test on 10" Carbon Steel Pipe Using Pulsed Imaging - Thermal Wave Imaging, Inc.

The importance of timing and processing of a thermal image is illustrated in this application. A section of 10" carbon steel pipe was tested with an EchoTherm pulsed active thermography system that included a flashlamp assembly, EchoTherm image processing, and a FLIR Prism DS PtSi FPA thermal imager. The section tested was adjacent to a hole in a pipe that also contained corrosion spots on the interior wall near the hole. The sequence was captured in real time (less than 10 seconds from flash to finished image). The three resultant images, shown in Figure 6-2, were obtained as the result of processing the images in three different ways. Consecutive thermal images taken immediately before the flash were summed by the software and then consecutive images taken after the flash were summed. The pre-flash images were subtracted from the post flash images to reduce emissivity artifacts and non-uniformity artifacts from the flashlamps. The image at the left is the sum of consecutive images; the image in the center is the result of subtracting the pre-flash images from the post-flash images; the image at the right is the result of additional differential subtraction of images taken at slightly different times.

The hole in the pipe wall can be seen in all three images. The shape of the area of corrosion, however, is most clearly evident in the center image. In the differential case at the right, an improperly applied subtraction results in an "inversion" effect, and the thin area surrounding the hole appears "cooler" than areas that are thicker.

This application illustrates the difficulty in selecting an ideal imaging condition when there are thick and thin sections on the same test article. Most practitioners advise capturing an entire sequence of images both before and after pulsed heat injection and then, selecting the image that best characterizes flaws at various depths. Wall thickness is then correlated to the time at which the images were taken with respect to the flash. An interesting alternative is the use of thermal "histograms," which sometimes provide less ambiguous information than thermograms. The interpretation of thermal histograms is discussed further in Section 6.6.

Another image of the same pipe wall corrosion sample is illustrated in Figure 6-3. Here the "time domain" thermogram is selected to correlate to the wall thickness of the pipe, and is then displayed in "3D" mode. The tallest peak is the hole and the other peaks are varying degrees of thinning due to areas of corrosion on the inside pipe wall.

For more information:

Thermal Wave Imaging (810) 569-4960 Steve Shepard

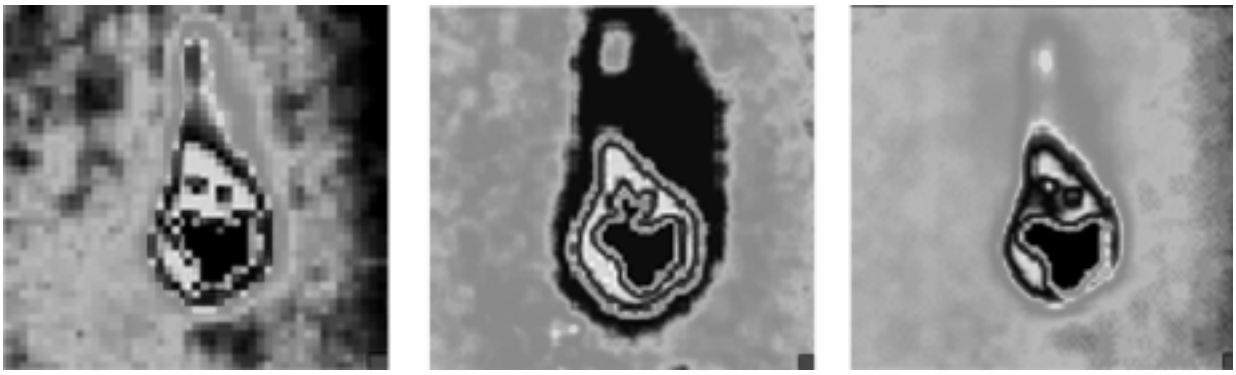


Figure 6-2
Processed Thermal Images of Corroded Pipe

In Figure 6-2, the image at the left is the sum of consecutive images; the image in the center is the result of subtracting the pre-flash images from the post-flash images; the image at the right is the result of additional differential subtraction of images taken at slightly different times.

Figure 6-3 is a time domain 3-D thermogram showing the hole as the tallest peak and additional corrosion thinning as the raised portions around it.

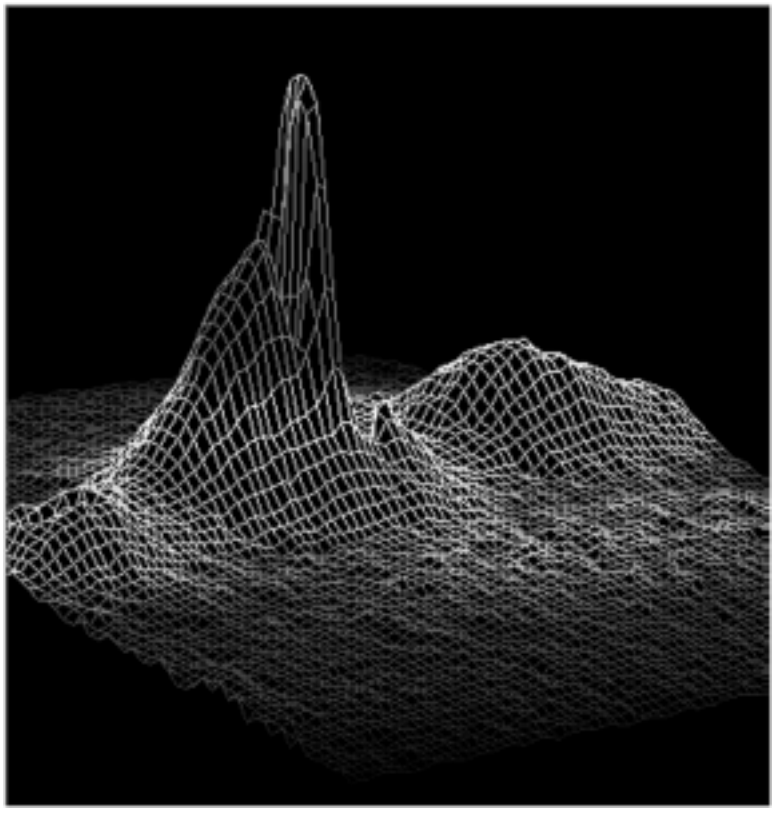


Figure 6-3
3-D Thermogram of Corrosion Thinning

6.3 Composite Epoxy Laminate Evaluation - Thermal Wave Imaging, Inc.

The evaluation of laminated materials and structures using active thermography is, perhaps, one of the earliest applications of the technique. The more recent use of time resolved active thermography on these materials, however, provides considerably more information regarding the depth of detected flaws.

Figure 6-4 shows three images of a section of impact-damaged 4mm-thick carbon-epoxy laminate. All thermograms were taken of the non-impact surface. The left-hand image is a conventional IR thermogram. The center image is a time-resolved thermogram showing the impact damage oriented in the direction of the ply. The right-hand image is a time-resolved thermogram with a longer gate time, showing the impact damage oriented in the direction of the ply (diagonal) and a deeper interply delamination (horizontal).

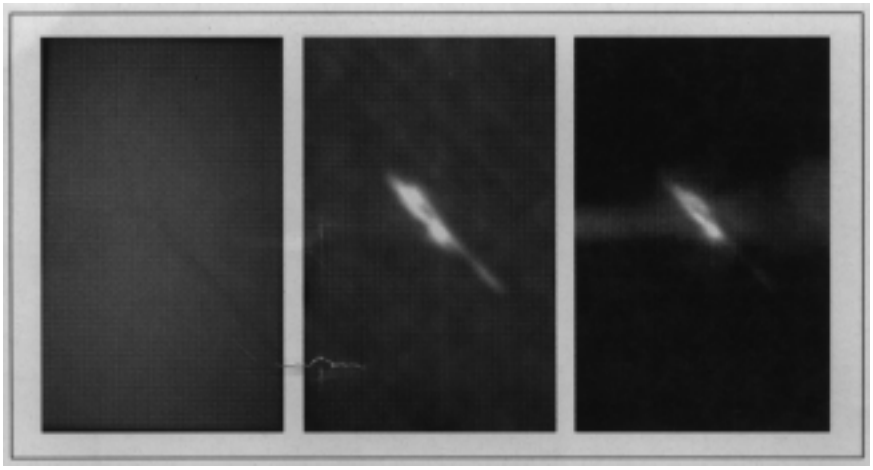


Figure 6-4
Images of a Section of Impact-Damaged 4mm-Thick Carbon Epoxy Laminate [9]

A sequence of time-resolved IR thermograms can reveal substantial information regarding the depth and severity of impact damage in epoxy laminates. Figure 6-5 shows a nine-image time-resolved sequence taken on the impact-damaged side of an eight-layer, 3.7mm-thick carbon epoxy fiber laminate. The upper-left image, taken at a 33msec time gate, shows impact damage in the ply direction (horizontal). At progressively longer gate times (left-to-right, top-to-bottom), the impact damage appears to follow the ply direction, which rotates 45° with each successive layer.

For more information:

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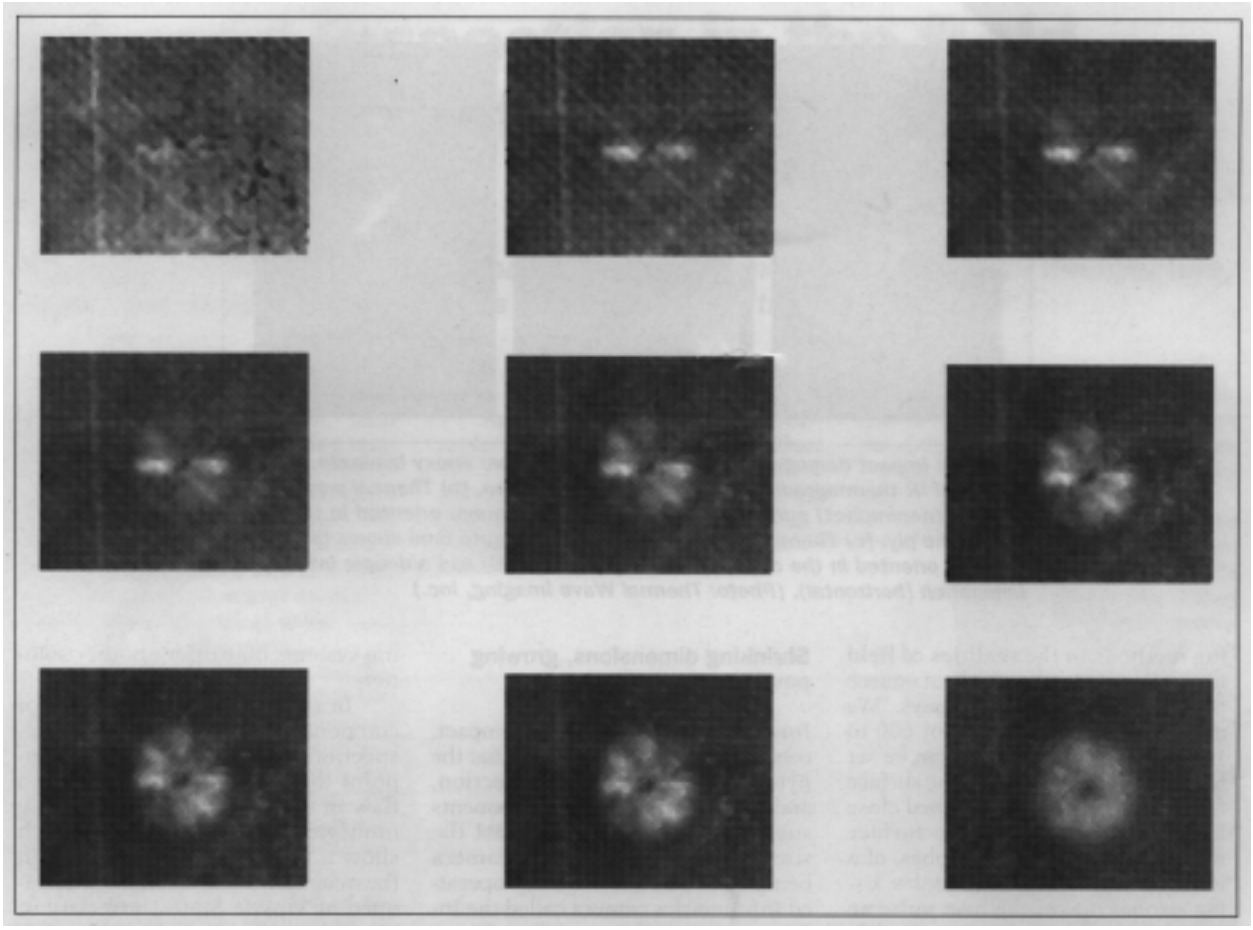


Figure 6-5
Nine-Image Time-Resolved Sequence Taken on the Impact-Damaged Side of an Eight-Layer, 3.7mm-Thick Carbon Epoxy Fiber Laminate [9]

6.4 Detection of Boiler Tube Corrosion and Erosion - Bales Scientific, Inc.

This application involved three tests on three prepared samples of representative boiler tube configurations conducted under laboratory conditions, followed by an in-situ test on an actual section of boiler tubing to verify the technique. The Pulsed Infrared Imaging equipment included a shrouded bank of xenon flash lamps with reflectors specially designed for enhanced flash uniformity, a CPU to synchronize the data collection with the flash lamps, and a Bales high resolution scanning imager.

The initial sample was a 4-inch long section of SA210-GrC, 2 inches OD x 0.220 inch wall thickness, containing a small defect caused by hydrogen damage. The defect (Figure 6-6) was sharply defined and appeared very early in the TRIR sequence, indicating that the defect had resulted in extreme thinning of the pipe wall. Defects causing lesser thinning would appear later in the sequence and would appear more diffuse.

The second sample was a section of five tubes split in half longitudinally. Four separate regions were milled into the original 0.220in IDs of four of the split sections. The resulting thermal image, selected so that all the defects appear simultaneously, is shown in Figure 6-7. The depths were, from the bottom up, (1) 0.030in., (2) 0.050in., (3) 0.070in. and (4) 0.100in. (on the lower 4 tubes). The image correlates well with the theoretical temperature model for the material and thicknesses involved.

The third sample was constructed by welding together, end-to-end, three sections of pipe with different thicknesses. The sections were, from left to right, sch80, double extra heavy (xxh), and sch40. Figure 6-8 shows the resultant thermal image with a horizontal line scan superimposed. This confirms that the center section was the thickest (lowest temperature) and the right-hand section was the thinnest (lowest temperature).

The in-situ test was run on an external section of sidewall penthouse tubing, 20ft. wide x 15ft. high, which had corrosion damage caused by a leaking roof. Ultrasonic testing had indicated reduced wall thickness. The thermal image (Figure 6-9) verified the presence of all the thinning detected by ultrasound and also indicated the extent of the thinning along the tubes. For comparison, Figure 6-10 is a thermal image, taken under the same conditions, of a section of new tubes, not as yet placed in service.

For more information:

Bales Scientific, Inc (510) 945-0144 Maurice Bales or Chip Bishop

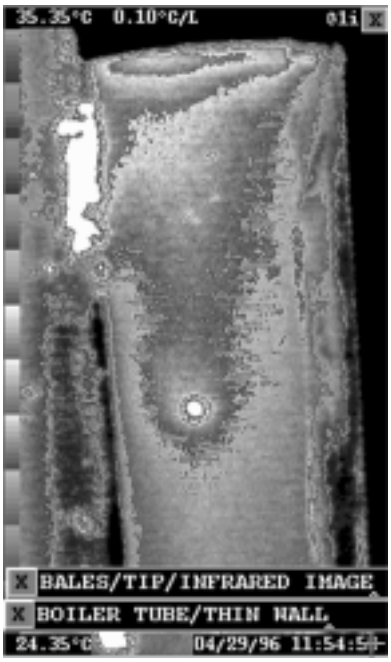


Figure 6-6
Thermogram of a 4in Section of Steel Pipe with Extreme Thinning

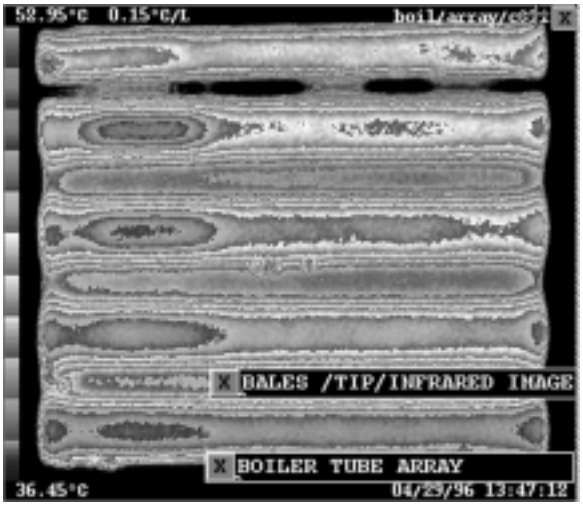


Figure 6-7
Thermogram of Prepared Split-Tube Sample with Increasingly Deep Milled Sections, from Bottom to Top, Cut Into The Lower 4 Tubes

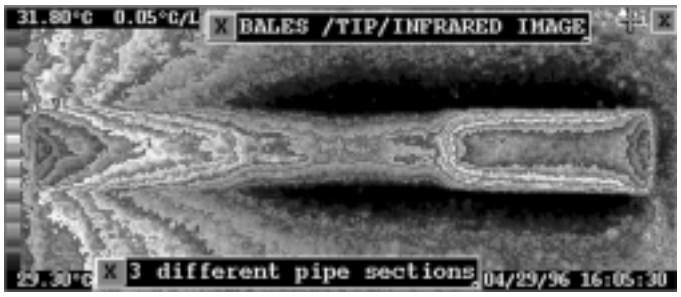


Figure 6-8
Thermogram of Sample Constructed by Welding Together, End-To-End, Three Sections of Pipe with Different Thicknesses, from Left to Right, Sch80, Double Extra Heavy (xxh), and Sch40

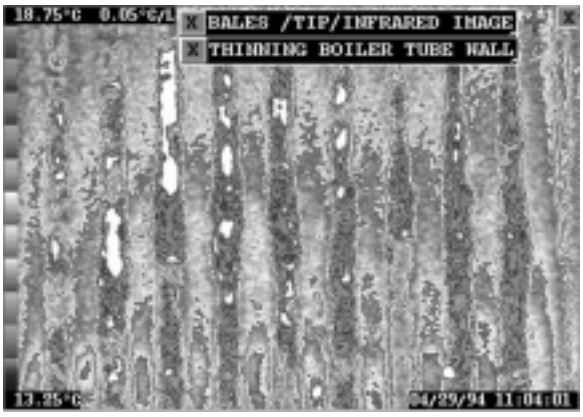


Figure 6-9
In-Situ Thermogram of Boiler Tube Section Indicating Areas of Thinning Due to Corrosion

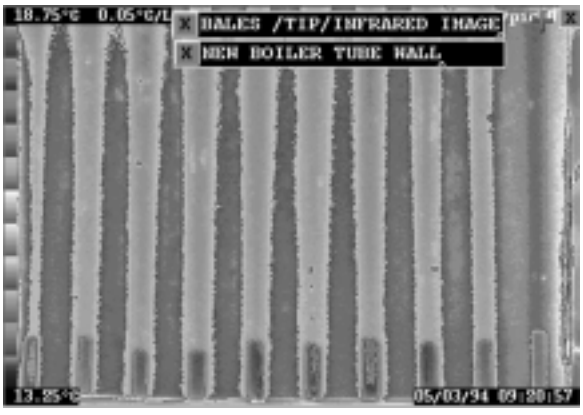


Figure 6-10
Thermogram of New Section of Boiler Tubing Not Yet Put into Service—No Thinning Indicated

6.5 Wall Thinning in Storage Tanks and Pressurized Vessels - Bales Scientific, Inc.

This test was run on samples of the bottom surface of a fuel storage tank in order to detect erosion/corrosion thinning on the under surface. The test simulated working from the inside of the tank, applying the heat pulse and recording the thermal images, while aiming down at the inside bottom surface.

The instrumentation configuration consisted of a Bales Scientific TIP (Thermal Image Processor) NDT Workstation, which includes the Bales high resolution scanning imager, a hood-mounted flash illumination source with custom-designed reflectors, a central processing computer, and Bales processing software. It was anticipated by the pretest heat flow calculations that corrosion thinning would result in very small temperature differences on the thermal images, on the order of 0.1°C. This made the thermal sensitivity specification of the imager (0.05°C), and the ability to minimize system noise, critical to the success of the test.

Based on the total field of view (TFOV) and spatial resolution (IFOV) of the imager, it was possible to determine the working distance such that the anticipated millimeter-size defects could be imaged with acceptable resolution. At a 1 meter working distance, the image was about 500mm wide and 333mm high with a resolution spot size of just under 1mm (0.83mm).

After setup, the actual test took a few seconds. A burst of 30 images was acquired after the flash and processed subsequently. Resultant sample thermal images are shown in Figures 6-11 and 6-12. Thinning defects result in earlier heat indications on the return images and, the more severe the thinning, the earlier the temperature will peak. Although the raw images indicate thinning flaws, there is also considerable noise present. Filters in the processing software were used to reduce the noise and to enhance the appearance of the images.

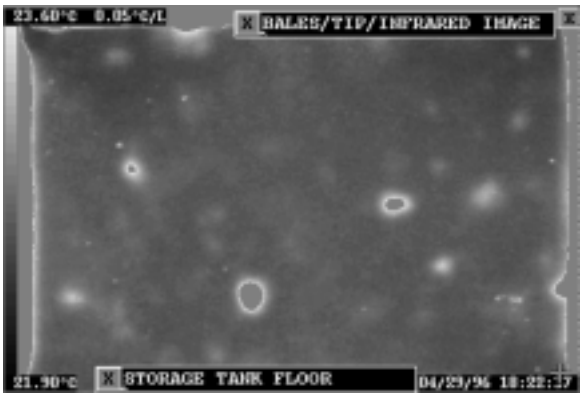


Figure 6-11
Raw Thermogram of a Sample Coupon Removed from Fuel Storage Tank Bottom Indicating Bottom Surface Corrosion



Figure 6-12
The Result of Processing and Filtering Raw Thermogram so as to Resemble a Photo of the Corroded Surface

Figure 6-11 is a raw image of a sample coupon removed from an in-service petroleum storage tank. Figure 6-12 is the result of processing the image to eliminate much of the background clutter and to further enhance the image such that it closely resembles a photo of the corroded (bottom) surface of the tank floor. The flaws detected represented corrosion thinning of 60%. This was confirmed by magnetic flux leakage (MFE) and B-scan ultrasonic testing. Further experiments at Bales indicate that thinning of as small as 10% can be detected using the IR method.

For more information:

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6.6 Selecting the Right Image in TRIR - Thermal Wave Imaging, Inc.

This experimental test was conducted in order to demonstrate some of the pitfalls in image interpretation in the use of TRIR with pulsed heat insertion. As discussed briefly in section 6.2, it is sometimes possible, particularly when image subtraction techniques are applied, to observe an apparent thermal inversion as exhibited in Figure 6-2, upper right. It should be noted that, although differential imaging is quite sensitive to changes in image contrast, in some cases, the polarity of the contrast might appear to be reversed due to large differences in the cooling rate. When this happens, a thinner area might appear cooler (instead of warmer) than a nearby thicker area of the same material composition. In some cases this can be avoided by studying the "stack of temperature histograms" rather than the "stack of thermograms" derived from pulsed heating.

The significance and the behavior of thermal histograms is illustrated in Figure 6-13. A thermal histogram is a distribution plot of temperature values. The x-axis represents the possible number of gray scale or color hue values, one for each image count, (a 12 bit image, for example, would have 2^{12} or 4096 possible temperature values), the lowest temperature value at the left, the highest temperature value at the right. The y-axis represents the number of pixels in the image of each grey scale value or color hue.

Immediately before the flash (left), the histogram shows a broad peak at lower temperature values and there are few pixels at higher temperatures. Immediately after the flash (center), the peak is sharp and shifted to higher temperatures as the near surface heats to its maximum value. As the near surface cools (right), the primary peak gradually broadens and moves toward lower temperatures, eventually returning to its unheated, steady state, location. In the case of a thermal "echo" from a disbond, a smaller, secondary peak appears on the thermal histogram at some finite time after the flash. The time delay is related to the material thickness or the depth of the disbond. The test involved the investigation of these secondary peaks on a prepared test sample.

A test sample was prepared from a 10-18 carbon steel bar machined on one side in steps to varying degrees of thinness ranging from 0.115in. to 0.336in., as illustrated in Figure 6-14. The sample was flash-heated with two 6400 Joule flashlamps and the image sequence was captured using a 12-bit InSb imager operating at 60Hz image frame rate as shown in Figure 6-15. The column of histograms at the right and the corresponding column of difference thermal images at the left were acquired at 0.25, 0.50, 1.00sec, and 2.00sec after flash and display the expected thermal behavior with broadened heating and reversion toward the steady-state condition. Each difference thermogram is the result of subtracting the preflash thermogram from the thermogram taken at the indicated time after the flash. The histograms, however, also exhibit secondary peaks corresponding closely to the milled steps in the sample. The appearance of the histogram peaks is far more pronounced than the steps in the difference thermograms.

Dynamic histogram analysis can be a fast, simple, and less subjective alternative to visual image selection and interpretation. Particularly in applications where high speed and repetitive monitoring of nearly identical parts is required, it can be applied to autonomous inspection, based on comparison to a compiled database of accepted samples.

For more information:

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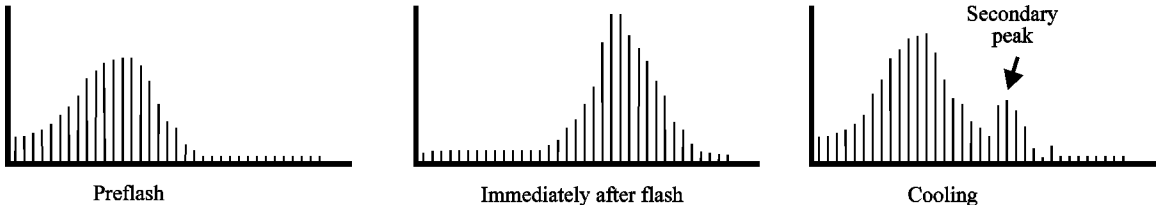


Figure 6-13
Behavior of IR Thermal Histogram During Flash Heating

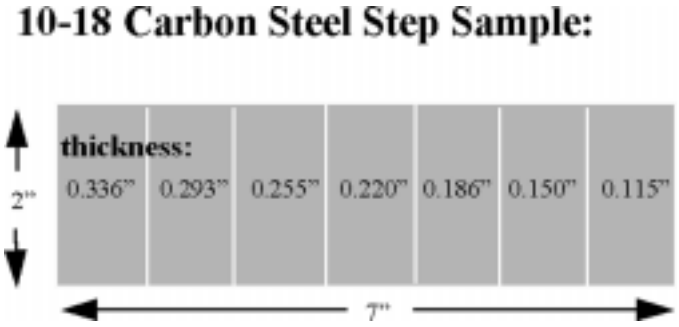


Figure 6-14
Diagram of Step-Milled Carbon Steel Sample

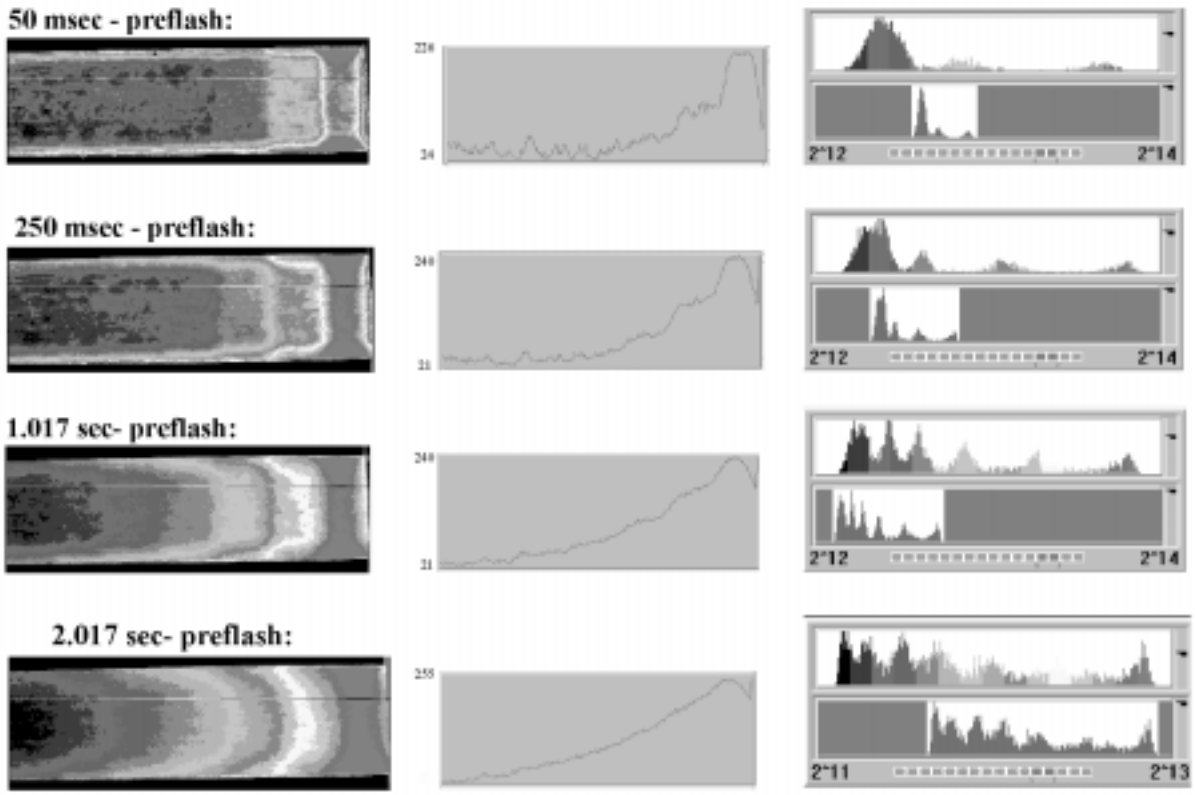


Figure 6-15
Time Sequence of Difference Thermogram, Line Scan and Histogram (from left to right). (Each difference thermogram is the result of subtracting the preflash thermogram from the thermogram taken at the indicated time after the flash.)

6.7 Thermal Wave Imaging of Aging Aircraft

Wayne State University and Thermal Wave Imaging, Inc.

Considerable work has been done by several groups involving the use of pulsed thermal injection to detect corrosion and disbonds in lap joints and butt joints in aluminum aircraft skin sections. Numerous papers have been published over the past few years on this subject, many of them by scientists at Wayne State University. The specific problems concerning aging aircraft are very much safety-related and these kinds of tests might very well become standard requirements in aircraft maintenance procedures in the future.

Since aluminum alloy has a relatively high thermal diffusivity, pulsed heat travels rapidly into the surface and thermal "echoes" in thin sections, such as those used in airframe fabrication, appear after very short time intervals. For this reason, high speed imaging systems are used in this application. Much of the earliest work was done using Inframetrics scanning imagers with 30Hz frame rates. Most of the current testing

employs IR focal plane array (IRFPA) imagers with 60Hz (or faster) image repetition rates.

In order to permit testing on actual aircraft, a portable, cart-mounted, pulse echo, thermal wave imaging system was assembled by the Wayne State / Thermal Imaging, Inc. Team for use in a hangar environment as shown in Figure 6-16. The basic elements were similar to those in the EchoTherm system described in section 6.2. The system was capable of imaging any exterior surface of the aircraft if suitable scaffolding was provided in the hangar.

Tests were run on a Boeing 737 aircraft in the FAA Aging Aircraft NDI Validation Center in Albuquerque, NM. For image acquisition, two timing gates were used for the aluminum alloy sample sections. The first gate was set for the calculated peak contrast time for the sample. The second gate was set at a time far out on the cooling curve. Typically, in aluminum alloy aircraft skins, the gate time for the first gate was set at five frame periods after the flash (this is 165ms for a 30Hz image repetition rate). The second gate was set at about one second after the flash. The averaged image (two to four frames) in the second gate was then subtracted from the averaged image within the first gate and the results were stored.

Figure 6-17 illustrates a lap splice region of the aircraft that exhibited no significant corrosion or disbonds. The rivet spacing is about one inch. The image shown in Figure 6-18 was taken from a different lap splice region of the aircraft and exhibited extensive corrosion.

Field testing has indicated that aircraft skin can be tested for corrosion and disbonds, using the system described above, at the sustained rate of about 30 meters / hour, making thermal IRNDT a promising technique for wide area NDI of aging aircraft.

For more information:

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Wayne State University (313) 577-2727 L.D. "Skip" Favro

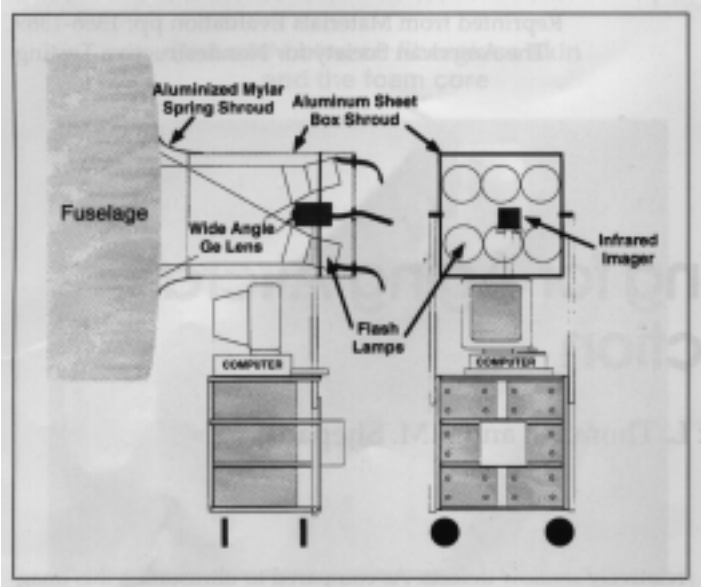


Figure 6-16
Schematic Diagram of a Pulse-Echo Thermal Wave Imaging System [10]

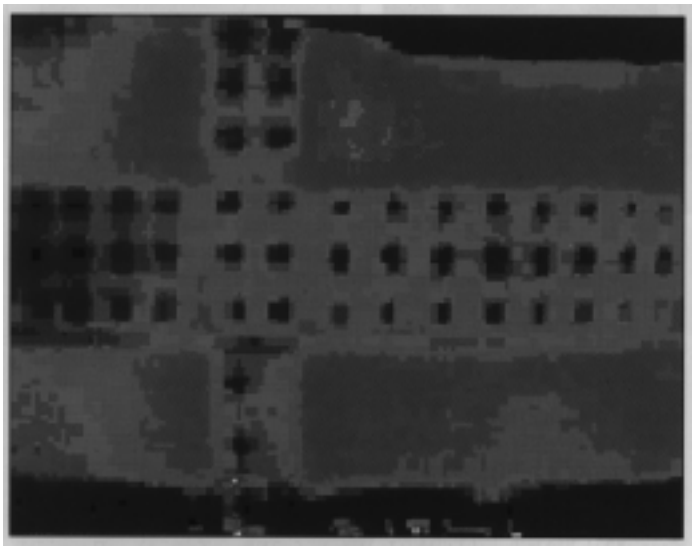


Figure 6-17
Thermal Image of Lap Splice Region on Aircraft Showing No Significant Corrosion or Disbonds [10]

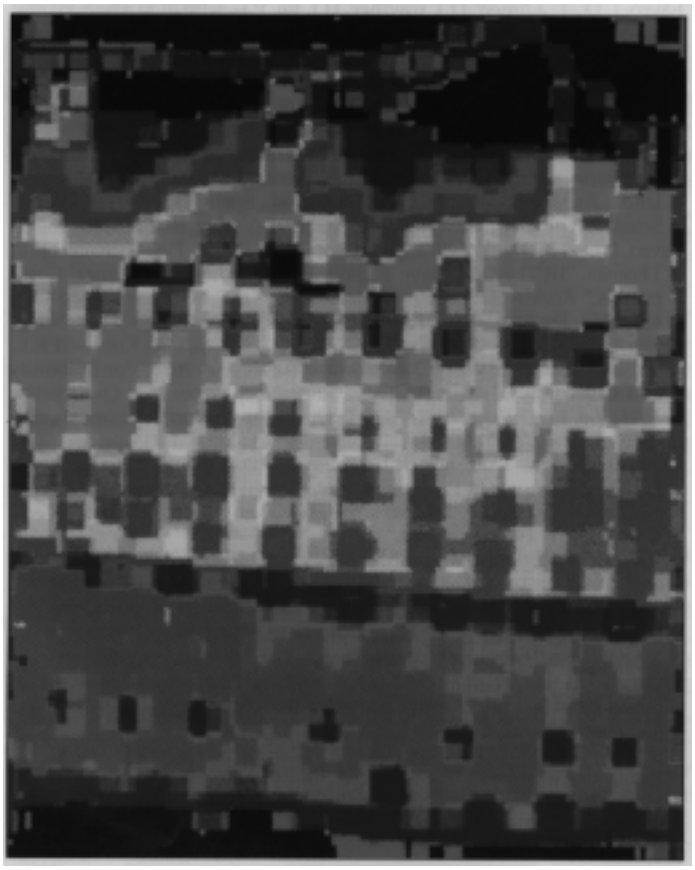


Figure 6-18
Thermal Image of Lap Splice Region on Aircraft Showing Extensive Corrosion [10]

6.8 Characterization of Disbonds Using Microwave Excitation - Johns Hopkins University

Scientists at Hopkins' Applied Physics Laboratory have been investigating various aspects of TRIR, including the different possible methods of non-contact heat injection. These include pulsed lasers (localized heating), pattern heaters (such as line heaters), area heaters (such as quartz lamps), and selective heaters (such as microwave sources). The most useful characteristic of microwave heating is that it selectively heats materials within a test sample in accordance with their relative microwave absorption characteristics. This test was performed on various samples using microwave excitation. Figure 6-19 illustrates the test configuration used for heating a sample panel with microwave energy.

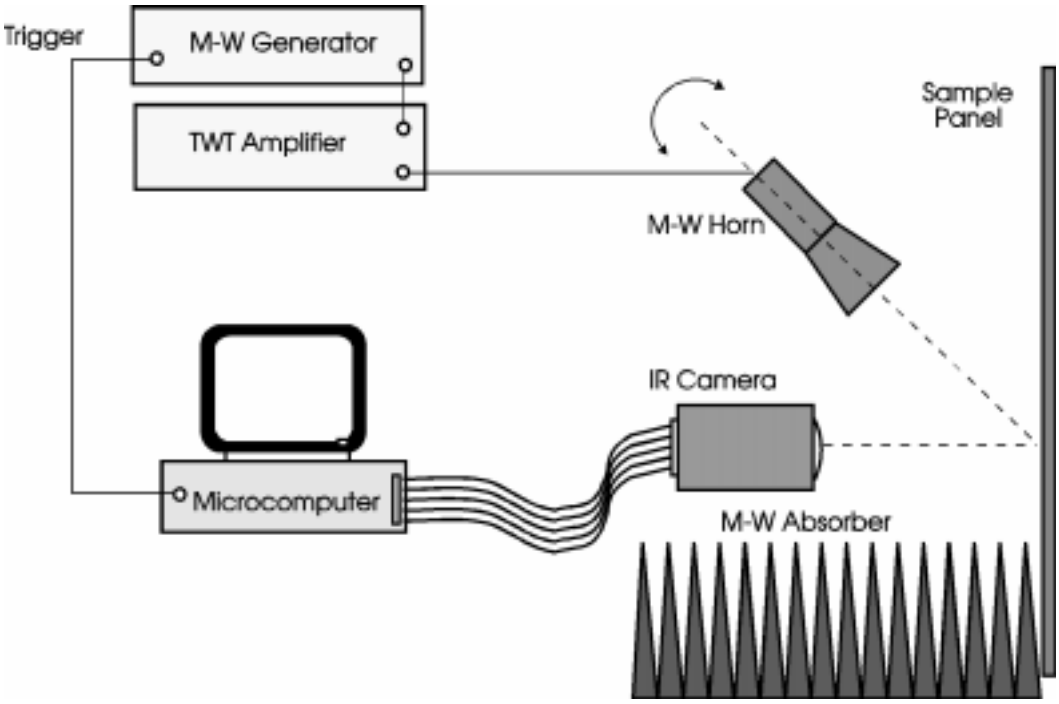


Figure 6-19
Experimental Setup for Microwave TRIR Measurements
(courtesy of Johns Hopkins University, Applied Physics Laboratory)

Microwave power at a frequency of 9GHz was provided by a traveling wave tube (TWT) amplifier, which amplified the power of a microwave source to deliver about 2.3 W into a single flare horn antenna from a coaxial feed. The antenna beam width was about 50° and, with the antenna placed 150mm (6 in) from the sample, the measured power was $7mW/cm^2$. Both the angle of incidence and the polarization of the microwave field relative to the sample were controlled by rotating and positioning the horn. The IR camera was a Santa Barbara Focal Plane 128x128 element InSb IRFPA imager operating from 3-5µm. The camera had a temperature sensitivity of 3mK and allowed frame rates of from 15 to 305Hz. The camera was synchronized with the source by triggering the microwave generator with the frame synchronization pulse from the camera.

Water is a strong absorber of microwave energy with relatively strong absorption at 9GHz. In gas pipelines, the epoxy-coating on the steel pipe used can become disbonded from the steel in certain locations and the disbonded area fills with water. To evaluate the applicability of the approach to detecting water-filled disbonds in epoxy-coated pipe, two samples of epoxy-coated pipe were tested, both with disbonds, one dry and one with water filling the disbond. Figure 6-20 illustrates the results after heating with a 10 second microwave pulse. The dry section (left) shows only a weak response in the disbonded area due to the poor microwave absorption of the epoxy

coating. The saturated section (right) clearly shows the contours of the disbonded area. The imaged area was 50mm by 50mm (2in. by 2in).

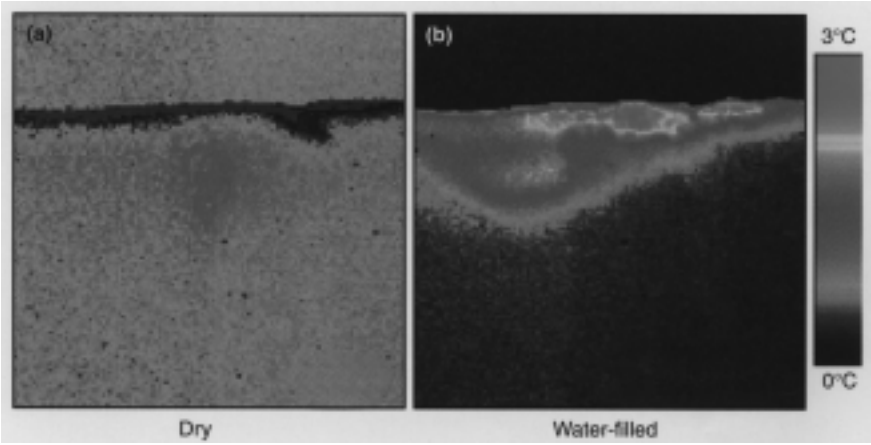


Figure 6-20
Infrared Images of a Disbonded Region of an Epoxy Coating on a Steel Pipe for Two Cases; Dry (left) and Filled with Water (right) [11]

Another application of microwave illumination to TRIR is the detection of carbon or metallic fibers in dielectric materials such as composite structures. The fibers are good absorbers and scatterers of microwave energy. The electromagnetic interaction depends on fiber length, thickness, and microwave polarization; the thermal response depends on the depth of the fiber in the material, its bonding to the matrix, and the thermal properties of the matrix. The dependence of the microwave-fiber interaction on fiber length is illustrated in Figure 6-21. Infrared images are shown of 100µm-wide fiber bundles with lengths ranging from 6 to 30mm, embedded in fiberglass epoxy.

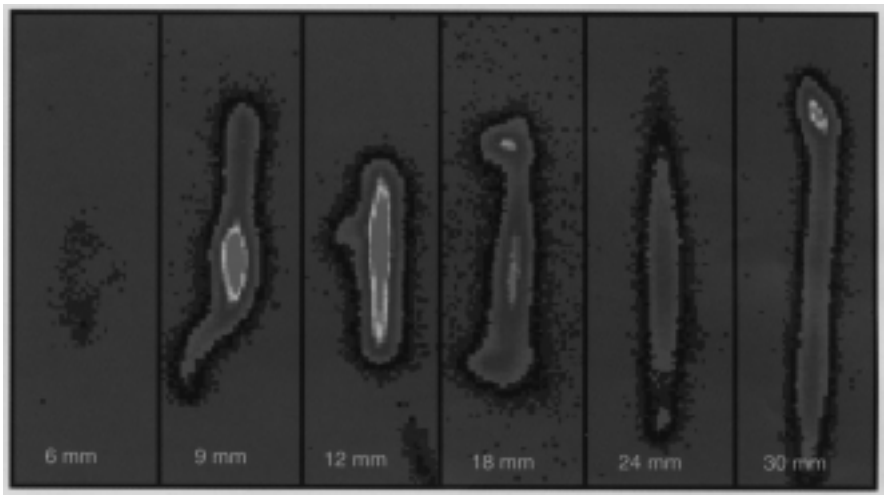


Figure 6-21
Infrared Images for Different Length Fibers After Microwave Illumination [11]

Small conducting defects of this type can occur during composite fabrication and can affect material properties. The use of TRIR imaging using microwave excitation can detect and identify these defects, determine the defect depth in the material, and establish the degree of bonding between defect and matrix.

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