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Capabilities and Limitations of Nondestructive Evaluation Methods for Inspecting Components Beneath Thermal Protection Systems

30 July 2004

Prepared by

O. ESQUIVEL
Space Materials Laboratory
Laboratory Operations

R. W. SEIBOLD
Space Launch Projects Directorate
Space Launch Support Division

Prepared for

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16. Abstract
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O. ESQUIVEL
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Laboratory Operations

R. W. SEIBOLD
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Prepared by

O. Esquivel
Materials Processing and Evaluation Department

R. W. Seibold
Space Launch Projects Directorate

Approved

E. C. Johnson, Associate Director
Materials Processing and Evaluation Department
Space Materials Laboratory
Laboratory Operations

E. K. Ruth, Systems Director
Commercial Launch Systems
Space Launch Support Division
Space Launch Operations

Abstract

The Aerospace Corporation was tasked by the Volpe National Transportation Systems Center to provide technical support to the Federal Aviation Administration, Office of Commercial Space Transportation (FAA/AST), to develop guidelines for inspecting components of reusable launch vehicles (RLVs) protected by thermal protection systems (TPS). The specific objective was to review nondestructive evaluation (NDE) methods used to inspect such aerospace structures covered by TPS. Basic issues concerning the inspection of components protected by TPS are identified, and the inherent strengths and limitations of the various NDE techniques as they relate to the projected needs of future RLV systems are described. This task also served to aid the identification and continuing development of advanced NDE techniques that offer strong potential for future application to RLV inspection. An improved understanding of the capabilities of current and developmental NDE approaches is necessary to establish future inspection guidelines unique to RLV systems. This report describes (1) generic issues associated with NDE inspection beneath TPS, (2) the current state-of-the-art of relevant NDE methods, and (3) new NDE techniques applicable to RLV inspection.

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1. Introduction and Summary

The need to assure the health and flightworthiness of reusable launch vehicle (RLV) structures is a fundamental concern for the success and safety of future commercial space launch ventures. Critical to achieving this assurance are the myriad material- and component-level inspection processes performed throughout the manufacturing, testing, and service life of these flight hardware systems. Among the most vital inspection processes are nondestructive evaluation (NDE) methods used for evaluating the quality of flight structures. The NDE methods enable inspection without damaging, sampling, or otherwise sacrificing the inspected parts.

Several NDE techniques are suitable for subassembly inspections; however, options narrow as material systems and subassemblies are integrated and accessibility for inspection becomes limited. Accessibility is particularly relevant to RLV flight structures covered with thermal protection systems (TPSs). Thermal protection systems provide necessary thermal barriers against harsh environments imposed during reentry or by other operational heat loads. As the external skin of the vehicle, TPSs play a crucial role in protecting critical structural elements. The design and capabilities of TPSs vary with location and vulnerability of the underlying structure. Various material systems may be used for TPSs, such as ablative or durable insulation coatings, bonded or sprayed multilayers, flexible blankets, or rigid refractory tiles. All of these TPS types can constrain access to the underlying structures for inspection. In some cases, removal and reapplication of the TPS may be required to inspect these structures. Where direct access to critical flight structures is unavailable or impractical, inspection processes that can penetrate through the TPS are needed.

This report presents a brief descriptive summary of various NDE methods relevant to the inspection of launch vehicle structures covered by TPS. Basic issues affecting the inspection of structures protected by TPS are identified, and the inherent strengths and limitations of the various NDE techniques as they relate to the projected needs of future RLV systems are described. An understanding of present NDE capabilities also serves to aid identification and guide development of advanced NDE techniques offering improved potential for inspection of future RLV structures.

Table 1-1 summarizes key features of the NDE approaches evaluated in this study and their suitability for inspection of TPS-covered structures. The assessments of suitability for this use are based on considerations of conventional application methods for and limitations of each NDE technique. This information and the detailed survey of NDE techniques presented in Section 3 will facilitate the selection of inspection criteria and flaw size requirements for specific TPS/structure configurations on future RLV systems.

Table 1-1. Summary of Capabilities for NDE Methods Evaluated in This Study

NDE Technique	Coverage	Penetration	Inspect Beneath Coating	Inspect Through Standoff Gap	Suitability for TPS-Covered Structures
Ultrasound	Point-to-point	Volume	Limited	No	Low
Acoustic emission	Entire part	Volume	Yes	Yes	Good (screening technique)
Eddy current	Point-to-point	Near surface	Yes	Limited	Good (limited TPS penetration)
Electromagnetic acoustic transducer (EMAT)	Point-to-point	Volume	Yes	Yes	Good
Microwave	Point-to-point	Volume	Yes	Yes	Unknown
Thermography	Full field	Variable	Limited	No	Low
Radiography	Full field	Volume	Yes	Yes	Good (Depends on flaw orientation)

2. Thermal Protection Systems and Underlying Structures

Two categories of launch vehicles, orbital and suborbital, are presently under development or manufactured by numerous companies and some governments around the world. Orbital and suborbital vehicles are those that are and are not, respectively, imparted with sufficient energy (and hence sufficient velocity) to achieve orbit around the Earth. Approximately 115 mi. is the minimal altitude required for placement into orbit. Suborbital RLVs are typically designed to achieve altitudes near 62 mi. As a comparison, commercial aircraft operate at altitudes below 18 miles.

The minimum velocity required to achieve orbit is roughly 30,100 ft/s. Suborbital launch vehicles are not designed to achieve these speeds and are generally much smaller than orbital vehicles and carry less propellant. As a consequence, thermal protection requirements for suborbital launch vehicles are significantly less severe than those for orbital vehicles.

2.1 Suborbital RLVs

A large variety of TPS designs, many proprietary to the RLV developers, are being employed for suborbital RLVs, such as those under development in competition for the Ansari X Prize.[1] The TPS designs range from none at all for systems designed for controlled descent (e.g., by parachute or in the manner of winged aircraft) to relatively thin layers of polymer, cork, foam, or composites for systems designed for rapid descent, with or without power.

A historical example is MI-15 low-density, room-temperature-curing ablator/insulator, which has been used extensively for thermal protection on aircraft and space launch vehicles. MI-15 is a filled elastomeric silicone, available in either a sprayable (Type I) or trowelable (Type II) form.[2] MCC-1 sprayable cork ablator insulation replaced MSA-2, Marshall sprayable ablator-2, as TPS on the Space Shuttle solid rocket boosters.[3] A family of materials designated low-temperature ablatives (LTAs) typically consists of three ingredients: (1) a resin such as polyester, epoxy, phenolic, bis-malimide, or polyimide; (2) a filler such as cork, microballoons, or silica; and (3) a chopped-fiber reinforcement such as polyamide, glass, silica, quartz, graphite, or boron.[4]

2.2 Orbital RLVs

Thermal protection systems are a crucial element of orbital RLVs, which generally cannot survive reentry into the atmosphere without substantial thermal protection. The ceramic tiles on the Space Shuttle Orbiter are a well-known example of such TPS. Representative TPS forms for orbital systems include quartz or silica blankets, silica or alumina tiles, carbon-carbon or silicon-carbide composites, and metallic panels. Example advanced TPS systems are described in Ref. 5.

An advanced, metallic TPS tile developed for the X-33 is shown in Figure 2-1. Tiles made of Inconel alloy are placed above insulator in a foil bag. The tiles are designed to be attached using a very simple approach and removable using only an Allen wrench to simplify maintenance and replacement.

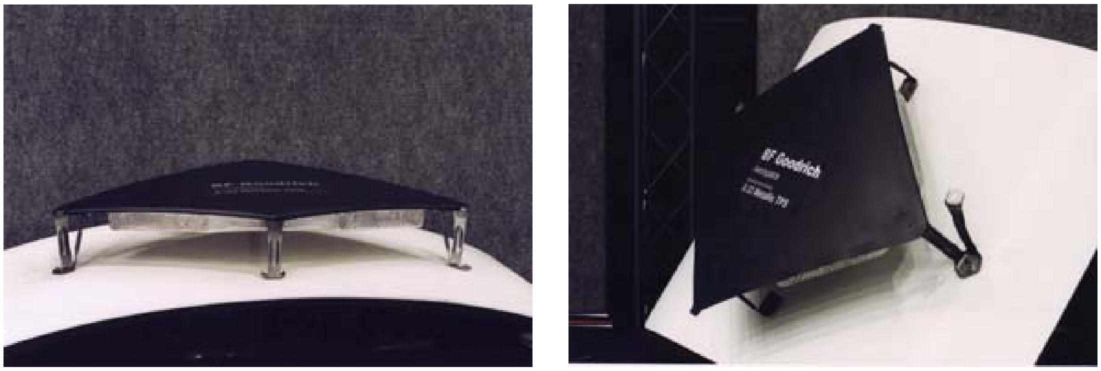


Figure 2-1. Metallic tiles developed for X-33. Photographs courtesy of NASA; used by permission.

Other metals are also used to create metallic tiles. Their primary advantages are strength, toughness, and low maintenance. Their primary disadvantage is a higher weight penalty compared to nonmetallic insulation tile structures. These advanced TPS designs are mentioned here to illustrate the potential need for NDE inspection across standoff gaps.

3. Survey of NDE Techniques

Nondestructive evaluation methods were assessed for interrogating structures beneath TPS on LVs and RLVs. Four specific NDE categories were evaluated: acoustic, electromagnetic, thermographic, and radiographic. Two subcategories of acoustic methods are ultrasonic inspection and acoustic emission monitoring. Three subcategories of electromagnetic methods are eddy current inspection, electromagnetic acoustic transducer (EMAT) inspection, and microwave imaging. For each NDE method, an overview is presented, followed by discussions of the basic equipment, the test techniques, advantages and disadvantages, and potential applications to TPS-covered structures.

3.1 Ultrasonic Inspection

Ultrasonic inspection is one of the most widely used NDE techniques. Its primary application in the inspection of metallic, composite, and other structural materials is the detection and characterization of internal flaws. It is also used to detect surface flaws, to define bond characteristics, to measure the thickness and extent of corrosion, and to determine physical properties, structure, grain size, and elastic constants. During ultrasonic inspection, beams of low-energy, high-frequency sound are introduced into a material; the sound waves travel through the material with some attendant loss of energy (attenuation) and are reflected at interfaces. The reflected (or transmitted) beam is detected and then analyzed to define the presence and location of flaws or discontinuities. Cracks, delaminations, shrinkage cavities, pores, disbonds, and other discontinuities that produce reflective interfaces can be easily detected.

3.1.1 Equipment

Most ultrasonic inspection is done at frequencies between 100 kHz and 25 MHz. The instrumentation required to perform ultrasonic inspection is readily adapted to remote field applications. The basic equipment typically includes: (1) an electronic pulse generator, (2) a transducer (probe) that emits a beam of ultrasonic waves when the pulse is applied, (3) a couplant to transfer energy from the transducer to the testpiece, (4) a receiving transducer to accept and convert the output of reflected ultrasonic waves from the testpiece to a burst of alternating voltage (a single transducer can alternately act as a sender and receiver), and (5) an electronic device to amplify and display or record the output from the testpiece. The couplant, typically water, oil, or a glycerin gel, is used to provide a suitable sound path between the transducer and test surface, eliminating any pockets of air that would reduce transmission of the sound beam. Smaller testpieces may be immersed in a water tank with transducers linked to an automated motion control system. The inspection of larger testpieces may employ bubbler or water squirter systems to couple the ultrasound to the surface. Field inspections with handheld devices are made when the area to be inspected is limited or difficult to access. In limited cases, the use of dry contact probes without couplant may be attempted.

When direct contact with the testpiece presents a problem due to concerns about surface contamination or non-compatibility with couplant material, an acoustic transducer specifically designed to minimize the transducer/air impedance can be used. This “air-coupled,” non-contact, ultrasound approach offers a means of performing automated inspections at high rates of speed without the necessity of an immersion bath or water delivery system.

3.1.2 Ultrasonic Testing (UT) Techniques

Ultrasound can be employed using various configurations or techniques that best suit the workpiece configuration or inspection constraints. One of the most common applications of UT is in the pulse-echo, normal probe reflection mode. The acoustic pulse is wholly or partially reflected by defects in the material and received by a single probe, which serves as both a transmitter and receiver. The time interval between transmission of the pulse and reception of the echo is used to indicate the distance of the defects from the probe (Figure 3-1).

The through-transmission mode of inspection uses two probes (transmitter and receiver) positioned on either side of the workpiece (Figure 3-2). The strength of the signal reaching the receiver will vary when hidden defects within the part block transmission of the signal. While detection of the presence

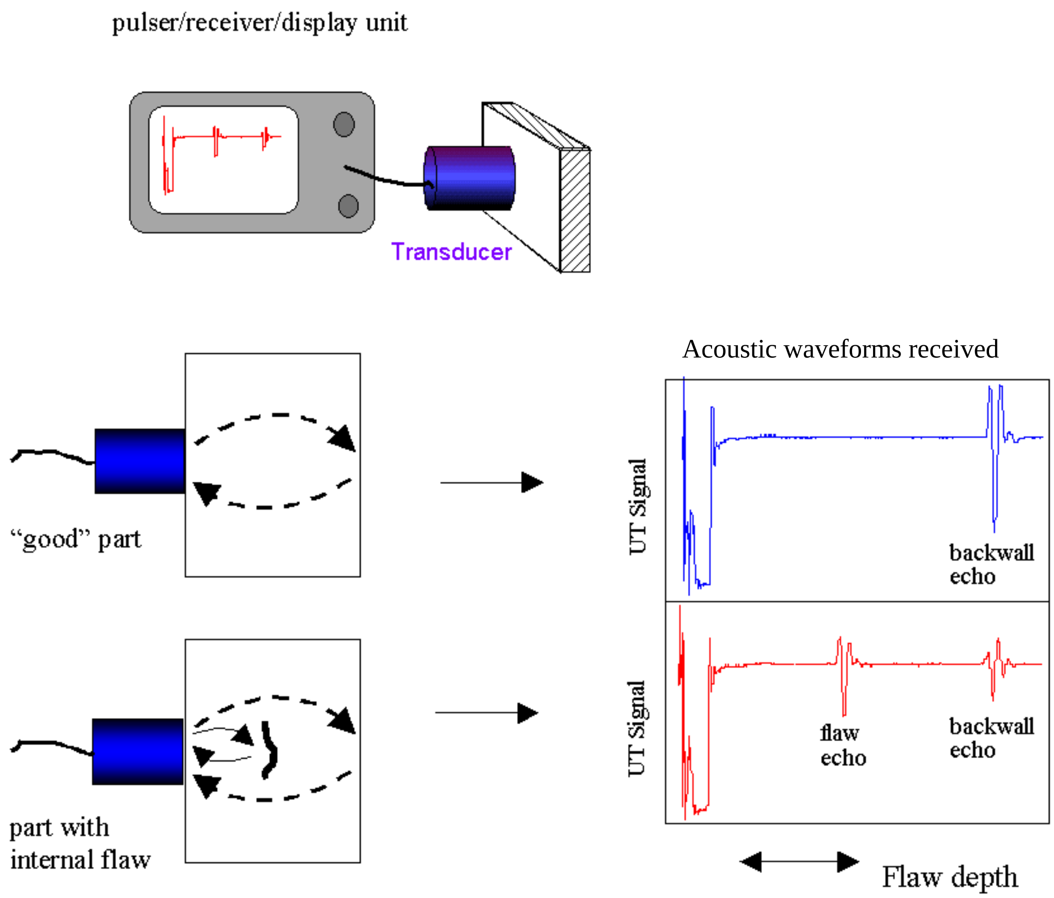
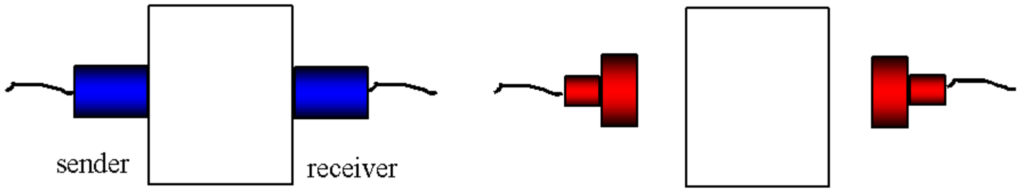
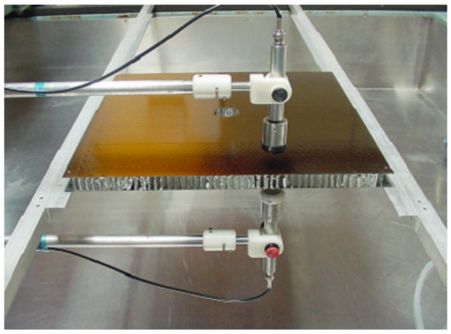


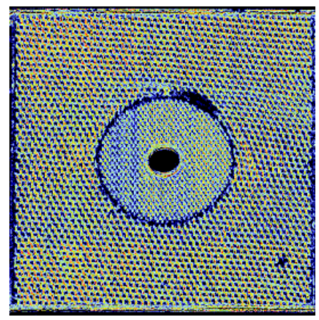
Figure 3-1. Ultrasonic inspection in pulse-echo mode (one-sided, single transducer).



Non-contact, air coupled transducers



Example of air coupled UT inspection



Resulting C-scan of honeycomb panel with insert

Figure 3-2. Ultrasonic inspection in through-transmission mode (two-sided, two transducers). Photographs courtesy Quality Material Inspection, Inc.; used by permission

or absence of flaws, based on receiver strength, is very straightforward, there is no indication of the depth of a defect. An advantage of this mode, however, is that highly attenuative materials, which prohibit single pulses from propagating through their thickness, may be probed using continuous wave (CW) or resonant tone techniques. A CW at the resonant frequency of the workpiece can be more efficiently injected by the transmitter. The presence of defects causes a change in resonance, decreasing the amplitude of the signal at the receiving transducer.

Other common UT inspection techniques include angle probe “pitch-catch” and surface wave inspection. In situations in which it is not possible to place a probe at right angles to a defect, such as in the inspection of butt welds in parallel-sided plates, sound is coupled into the part at an angle using an angle wedge. As depicted in Figure 3-3, the sound beam can propagate, reflecting from workpiece surfaces, until a weld flaw (or any out-of-plane flaw) reflects the sound back to the probe (angle probe reflection) or interrupts the transmission to a receiver (pitch-catch). The angle probe(s) scan forward and back from the weld to inspect the full thickness of the weld.

A surface or Rayleigh wave can be transmitted efficiently for long distances across the surface of a workpiece with contoured surfaces (Figure 3-4). Surface wave inspection is particularly suited for inspecting for surface flaws in remote or inaccessible regions of a workpiece.

Another important aspect of ultrasound inspection is that material characteristics other than distinct cracks or flaws may be detected by the manner in which the sound interacts with the particular mate-

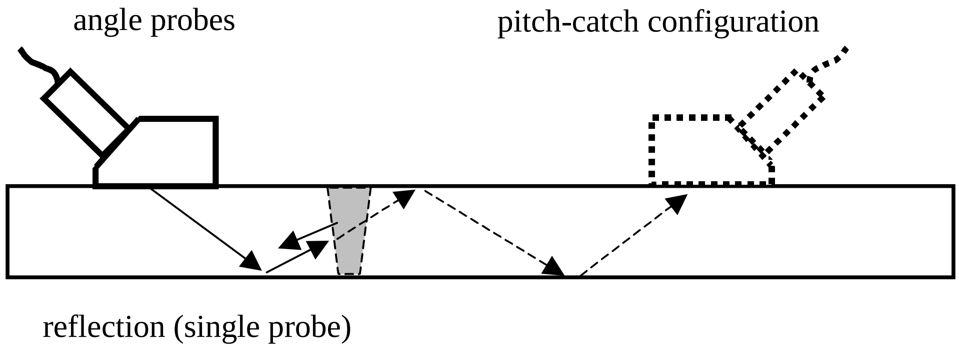


Figure 3-3. Angle probe “pitch-catch.”

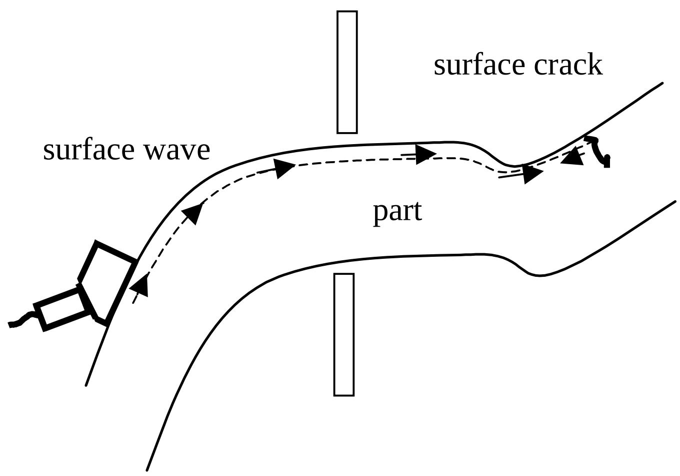


Figure 3-4. Surface wave inspection.

rial condition. For example, UT can be used to distinguish the degree of corrosion in surfaces that may not be accessible for visual inspection. The extent of corrosion and pitting can be assessed by the degree to which an incident acoustic beam is scattered by the roughened surface back to the transducer. Ultrasound inspection can also be used to distinguish grain texture (size and shape) in alloys that are rolled or forged. The nature of the grain structure along the short transverse direction (maximum distortion) causes considerably more acoustic scatter, or grain noise, between backwall echo signals than in the other orthogonal directions. This technique has been used to confirm proper orientation of critical strength parts. Schematic depictions of these applications are shown in Figure 3-5.

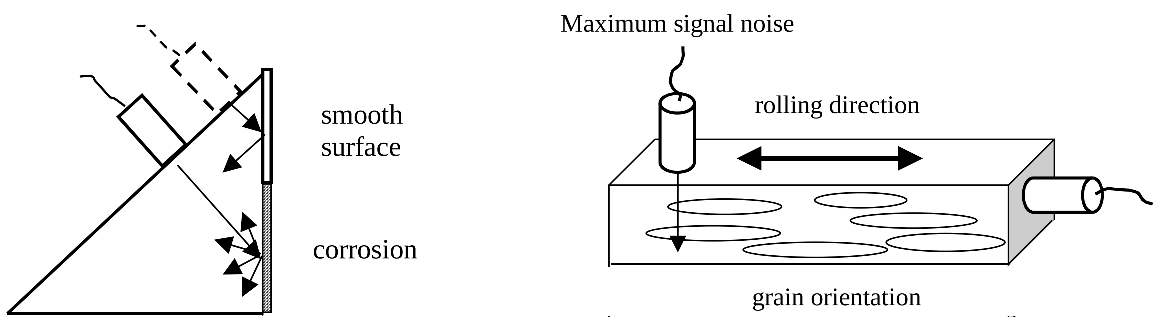


Figure 3-5. Evaluation of material characteristics using ultrasonic inspection.

3.1.3 Advantages and Disadvantages

The general advantages of ultrasound as compared to other NDE methods include:

- Volumetric scanning ability, enabling inspection of a volume of material extending from front surface to back surface of a part.
- Penetrating power, which allows detection of flaws deep in a testpiece, particularly in metals.
- High sensitivity, permitting detection of very small flaws.
- Greater accuracy than other NDE methods in determining the position of internal flaws, estimating their size and characterizing their orientation, shape, and nature.
- Only one surface needs to be accessible.
- Portability, adaptable to field use.

Disadvantages include:

- Single-point measurements (transducer must scan or raster to cover the surface of a testpiece).
- Nonmetallic parts (such as some composite materials) may exhibit high acoustic attenuation, making detection of deep flaws difficult.
- The test surface must be compatible with couplant material (except in cases of dry contact or air-coupled ultrasound, where no couplants are used).

3.1.4 Applications to TPS Configurations

Ultrasonic methods offer several unique advantages for inspection of many alloy systems used in advanced aerospace structures. However, its application to the inspection of materials commonly used for thermal protection, or for penetration beneath TPS, may be limited. This is primarily due to the poor propagation of sound in low-density, porous, insulator materials. If a thermally insulating material is fabricated in a manner that results in a highly porous structure (carbon or polymer foams, for instance), the injected ultrasound beam is attenuated by the high degree of internal scattering. In ceramic and composite structures, acoustic absorption is generally higher than in metals, and the propagation of sound becomes difficult at high frequencies. Propagation of sound energy in these materials improves at low frequencies; however, the discrimination of small flaws becomes more difficult at low frequencies. Ultimately, the effectiveness of an ultrasonic approach is subject to a wide variation in responses, and these variations are highly dependent on the structure and properties of the testpiece.

Some advanced thermal protection concepts may employ tile elements of high temperature resistance metal alloys that may be inspected for flaws using an ultrasonic approach. However, if there are appreciable standoffs, or air gaps beneath the metal tiles, propagation of ultrasound from the surface to underlying structure is not likely. Ultrasound inspection of an underlying surface is possible when a probe tip can penetrate through the covering layer at discrete locations. This approach has been used to assess the health of graphite-epoxy composite solid rocket motor cases in regions where an overlay of cork is used as a thermal barrier. Potentially, advanced TPSs that employ standoff configurations may allow for subsurface ultrasonic probe inspections in areas where access must exist to allow for subsequent thermal expansion, for instance, at gaps between high-temperature tiles. Methods for injecting and detecting ultrasound across overlays (or gaps), without sound propagation through the overlay, are treated in Subsection 3.4 on EMAT methods.

3.2 Acoustic Emission (AE) Inspection

Acoustic emission (AE) inspection differs from most other NDE techniques in that the key signals acquired to assess the health of the test article are generated within the material itself, not from an external source as in the case of ultrasonic or eddy current inspection. Also, while most other techniques detect geometrical discontinuities or flaws, AE detects the movement, or growth, of discontinuities. Acoustic emissions are stress waves produced by defect-related deformation processes such as plastic flow and crack growth. AE monitoring is the process of electronically "listening" to these emissions as they propagate through the structure, typically under a specific load cycle.

A major benefit of AE inspection is that it allows the whole volume of the structure to be inspected nonintrusively from a few sensor sites, instead of scanning the entire structure to look for local defects. Typically, a global AE inspection may first be used to screen critical areas within a complex structure, then, if necessary, other NDE techniques may be used in local areas to identify the nature of the located defects. AE inspection is applicable to a variety of metallic and nonmetallic materials that emit and propagate acoustic signals caused by growth of cracks, delaminations, deformation and corrosion processes, phase transformations, and other microscopic deformations. Active development in the field of AE in recent years has advanced the state-of-the-art for discrimination of emission signals (noise filtering, waveform parameters) and interpretation of emission sources (analysis of mechanisms that generate emissions), to make AE a vital NDE tool for structural testing, in-process monitoring (welding, leak testing), and integrated health monitoring and fatigue crack detection (aircraft systems).

3.2.1 Equipment

Because AE is particularly well suited for the inspection of large, complex structures, the basic equipment is generally tailored for in-service field use as well as controlled laboratory testing. The key hardware elements are: AE sensors (piezoelectric crystal transducers), amplifiers, cabling, signal detection instrumentation (filters, counters, signal digitizers), and a computer for signal parameter processing, analysis, and display (Figure 3-6). Often, during structural proof testing for instance, data may be collected and stored during load testing, then analyzed and assessed for significant emission activity following the test. An AE system may be integrated into on-line processing equipment for real-time assessment and feedback control of welding operations, pressure vessel and pipe leak testing, or for continuous monitoring in nuclear reactor systems and aircraft. As with ultrasonic testing (UT), the AE transducers must necessarily be well contacted to the testpiece surface, typically with the use of a couplant medium. Unlike UT transducers that must scan the surface, the AE transducers can be firmly attached (taped, bonded) at a single site. An array of transducers offers the vital

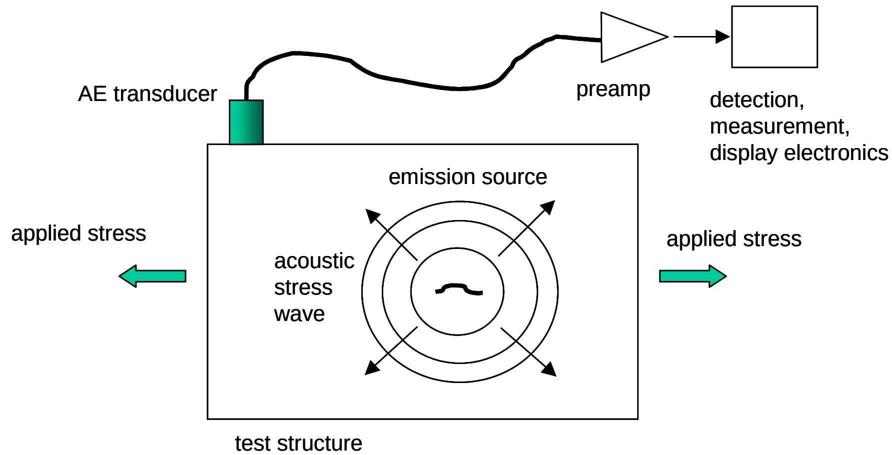


Figure 3-6. Schematic depiction of acoustic emission generation and acquisition.

advantage of emission source location, either through a zone coverage approach or by point location and triangulation based on the arrival times of the detected signals. AE systems are available with up to 100 sensor channels, depending on the size and complexity of the test structure. Typically, most testing is accomplished with 12 to 32 channels. Precautions against interfering noise are a major consideration in an AE inspection setup. The typical frequency range for most AE monitoring is 100 to 500 kHz (in some applications up to 2 MHz). Acoustic background noise from external sources (movement of structures, impacts, pump vibrations, electrical sources, etc.) typically imposes a low-frequency limit to the detection window, while the upper frequency limit is constrained by attenuation of the constituent materials. Recent advances in waveform analysis can allow contributions of non-emission signals to be filtered out.

3.2.2 AE Inspection Techniques

The basis for AE inspection is that microstructural processes in a material system (such as yielding, twinning, microcracking, delamination, fiber breakage, etc.) are activated under load to produce transient acoustic signals that can be monitored when they propagate to the surface. Understanding the complex acoustic waveforms that arrive at the surface, and associating these waveforms with specific internal emission sources, form the basis of continuing development in AE technology. As a long established and accepted NDE approach, traditional methods of AE have involved the processing of discrete emission events as defined by threshold-crossing criteria (minimum voltage amplitude of the acoustic signal). Simply presenting the cumulative number of events, or the count rate of events as a function of time or load history, was one of the primary ways to quantify AE activity. Figure 3-7 illustrates typical history plots of AE data versus load. A “good” metallic part may show relatively little emission activity under an applied load until, ultimately, local plastic strain develops and general yielding occurs with rapid crack propagation prior tensile failure. A “bad” part may exhibit emission activity much earlier in the load cycle due to high concentration stresses at internal flaws, activated microcracking at corrosion sites, or the presence of embrittled phases. The presence of such flaws will typically be detected by the AE “count” signature at loads well below those required to damage the part. Thus, AE inspection can be used to screen for bad parts, much like proof testing, without risking damage to “non-flawed” components.

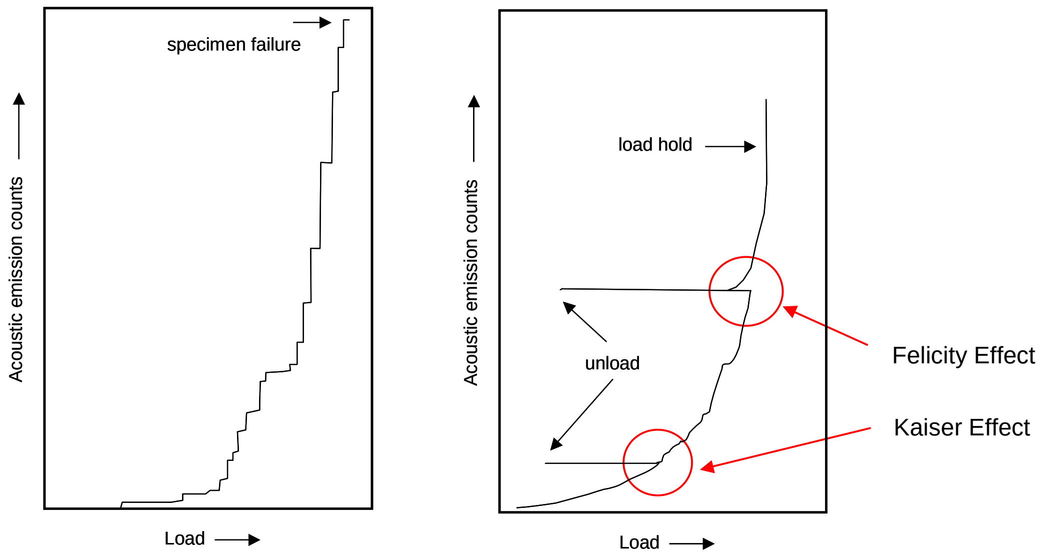


Figure 3-7. Plot of typical AE data versus load.

Since emission activity emanates from various forms of microstructural strain release, the process is irreversible after the load is released, i.e., no AE is generated on repeated loading until the load exceeds the maximum prior level experienced by the part. This "Kaiser effect" and the related "Felicity effect" at high stress levels are useful for discerning emissions from stable, structurally insignificant defects (relief of residual stresses, localized yielding) as opposed to unstable, structurally significant defects (crack growth).

Another important AE data format is the source location display. Based on the arrival time of coordinated emission signals from multiple sensor sites, a planar map of emission sources can be composed, as shown in Figure 3-8. The true strength of AE inspection is that the locations of potentially impor-

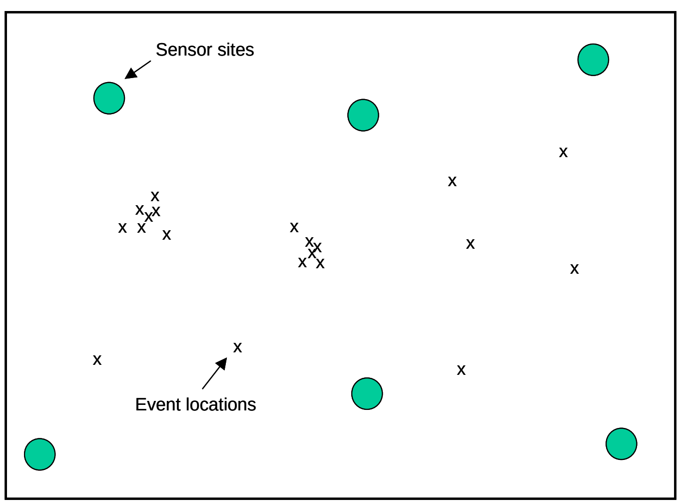


Figure 3-8. AE source location map identifying two regions, each with a cluster of emission data.

tant flaws (high AE activity) in large structures can be determined, and with subsequent detailed inspection using alternate NDE methods (ultrasound, eddy current, radiography, etc.), an assessment of flaw criticality (type, size, etc.) can be made.

While the principle of "listening" to a component's response under a state of stress offers an important technique for assessing structural health, making sense of the vast and high rate of acoustic data collected is an important concern. With advances in high-speed data processing, discrimination in emission monitoring has evolved from simple event-count processing to multiparameter hit descriptions and modal wave analysis. These advanced processing approaches contribute to elimination of the overlay of noise, sensor bias, spectral dispersion, and other complexities.

3.2.3 Advantages and Disadvantages

The general advantages of acoustic emission inspection as compared to other NDE methods include:

- An entire structure can be tested at once to locate potentially critical flaw sites.
- Access to the structure is required only at a limited number of sensor sites (typically 6 to 32 transducer channels).
- Less intrusive on workpiece or processing operations. Inspection is passive and can be incorporated into proof testing or operational loading configurations.
- Technique is typically more sensitive to defects than other NDE methods.
- Less sensitive to testpiece geometry than other techniques.
- Portability, adaptable to field use.

Disadvantages include:

- Requires stress cycling or loading to activate emission sources.
- Acoustic transducers (AE sensors) must contact the surface (directly or via acoustic waveguide).
- Each inspection/loading is unique (flaws are affected by each inspection/loading).
- Emissions can be ambiguous, subject to interpretation.
- Noise signals (electronic, acoustic, material related) can make flaw emissions difficult to distinguish.
- Requires intensive electronic signal processing and data storage (electronics hardware, computer).

3.2.4 Applications to TPS Configurations

Acoustic emission inspection presents a potentially effective NDE approach to interrogate the general health of structural elements covered or overlaid by TPS. The basic requirement is that AE sensors be periodically or permanently attached to the structural members at selected sites. The sensors, however, need only be “acoustically” attached to the structure. That is, an intermediate “waveguide” may be used, or some means to pipe the sound from the structure to the sensor (small contact probes inserted between TPS segments, for instance). Or attachment may occur through the interior of the structure. To “inspect” the structure, appropriate loading must be imposed that either (1) activates emission activity for source location analysis, or (2) ensures that no significant emission is detected under load conditions relevant to flight safety. The greatest concern for this application, as for all AE applications, is the ability to distinguish acoustic activity emanating from material “flaw” sources from activity caused by non-relevant sources (extraneous noise, loading rig, etc). Development of specific AE methods for this case should address this concern. A current trend in advanced aircraft health maintenance is to incorporate an AE system as an on-board diagnostic monitoring system. This approach, while not a substitute for comprehensive structural assessment, allows insight into the response under actual flight stress conditions.

3.3 Eddy Current Inspection

Eddy current inspection techniques are based on the generation or induction of electrical eddy currents in a workpiece and understanding how these eddy currents respond to the presence of flaws or changes in material conditions. Since the method is based on electromagnetic induction, the target materials must be electrically conducting to some degree and are most often metals, structural alloys, or graphite fiber composites. Eddy current methods are highly versatile and can be used to detect surface and subsurface cracks, voids, inclusions, and effects of corrosion. This technique can be used to assess material thickness or thickness variations in surface coatings, as well as changes in electrical conductivity, grain size, hardness, heat treatment conditions, and a variety of other compositional and microstructural conditions. Since the eddy currents are induced by the proximity of a probe coil, direct contact with the workpiece is not required. Thus, the technique can be adapted to automated, high-speed scanning configurations, or where non-contact methods are desired due to contamination sensitivity. Because the eddy current signal response (monitored as the change in probe coil impedance) is sensitive to a wide range of structural, physical, and geometrical characteristics, one important concern is the ability to distinguish flaw-related signal changes from those due to other non-flaw, material variables. This, however, can be addressed through appropriate inspection development procedures and the use of suitable material defect standards.

3.3.1 Equipment

The equipment for performing eddy current inspection can vary in complexity, but typically consists of (1) a search coil probe element, which, when energized with an AC current, induces eddy currents in a conductive workpiece; (2) a variable-frequency voltage generator to excite the search coil (typically within the frequency range of 1 kHz to 5 MHz for nonmagnetic materials and at lower frequencies for ferromagnetics); (3) a phase-sensitive voltage detector to measure coil impedance change induced by the eddy currents in the presence of defects; and (4) an x-y oscilloscope for the phasor display of coil impedance change (or other representations of the response signal). The generation, detection, and display electronics are typically incorporated into a portable eddy current inspection unit to which various types of hand-held inspection coil probes can be attached depending on the nature of the inspection (described in further detail below). Commonly, variations of these basic functions are incorporated into line-production, fixed-station inspection units for tubing fabrication, or other continuous manufacturing inspection applications.

While the basic instrumentation required for performing eddy current inspection is relatively straightforward, proper interpretation of the response signals requires careful consideration of inspection parameters such as probe alignment relative to the test surface, probe contact or liftoff consistency, and appropriate selection of setup parameters (excitation frequency, probe configuration, etc). Specially designed probe fixtures and appropriate material defect standards that emulate the maximum allowable flaw size should not be overlooked as essential elements for eddy current inspection.

3.3.2 Eddy Current Techniques

When a coil carrying an alternating current is placed in proximity to a conductive material, eddy (or circular) currents are induced within the material. These induced currents produce a magnetic field that is in opposition to the primary magnetic field surrounding the coil (Lenz's law). This interaction between fields causes a back electromagnetic force (emf) in the coil and, thus, a change in the coil impedance value. If a material is uniform in composition and dimensions, the impedance value of the probe or search coil placed close to the surface should be the same at all points on the surface. If the material contains a discontinuity (surface or subsurface crack), the distribution and magnitude of the eddy currents will be altered in the vicinity of the discontinuity. With this change, there will be a consequent reduction in the magnetic field associated with the eddy currents, so the coil impedance value will be altered. Two of the more common configurations of search coils are the flat or pancake type coil used to examine flat surfaces and the solenoid type coil used to surround cylindrical parts or inserted in a bore of tubing (Figure 3-9). A schematic representation of the effect of a discontinuity on the eddy current pattern is shown in Figure 3-10.

Sometimes two or more search coil elements may be employed, where one functions as a driver to induce eddy current and another to detect (reflection probe). In an "absolute" configuration, one coil samples a "good" reference specimen, while a differential signal is created with an identical coil on a test specimen. To eliminate non-defect-related variables, two adjacent coils may be used to compare

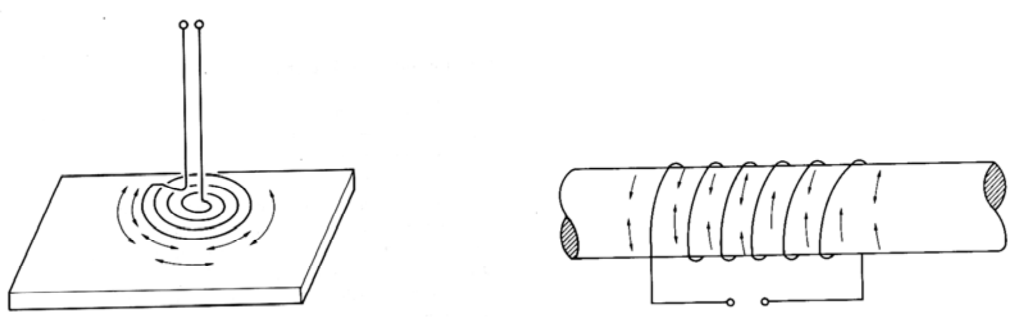


Figure 3-9. Examples of probe coil configurations: Pancake probe for flat surfaces and solenoid coil for tubular parts. Source: Ref. 6; used by permission.

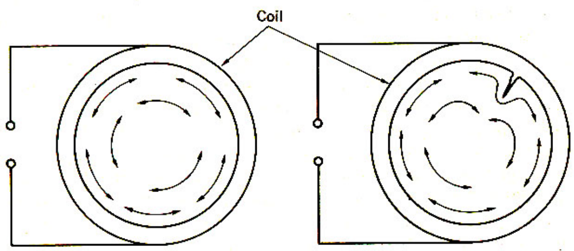


Figure 3-10. Pattern of eddy current in a "good" part, versus disruption of eddy currents in presence of a crack. Source: Ref. 6; used by permission.

regions on the same part. This "differential" configuration is insensitive to common variables (i.e., gradual dimensional variations), while abrupt discontinuities (cracks) will be very apparent under each coil scan.

The electrical conductivity of a material is one of the major parameters in eddy current testing. Because the resulting coil impedance is a strong function of material conductivity, any material condition that affects conductivity may also be monitored by the eddy current response. Minor variations in alloy chemistry, cold working, heat treatment, and surface temperature will influence eddy current response. Changes in material hardness can often be discriminated using eddy current inspection.

Because eddy currents are induced by a varying magnetic field, the magnetic permeability of a material strongly influences the eddy current response. In non-ferromagnetic materials, the secondary electromagnetic field is derived solely from the induced eddy currents. In ferromagnetic materials (some steels and alloys of iron, nickel, and cobalt), the additional magnetic effects, due to their variable and high relative magnetic permeability, are of sufficient magnitude to overshadow the field effects produced by eddy currents. However, by magnetizing ferromagnetic parts to saturation (constant permeability), these effects can be minimized. Inspection of magnetic materials is typically performed within a magnetizing coil carrying direct current of a value to achieve saturation.

The distribution of eddy currents induced within a part by the probe coil decreases exponentially with distance from the surface. This "skin effect" is typically quantified by a parameter called the standard penetration depth, S, which is a function of the material resistivity and magnetic permeability, and the frequency of the excitation current. Figure 3-11 depicts distortion of the eddy current field with

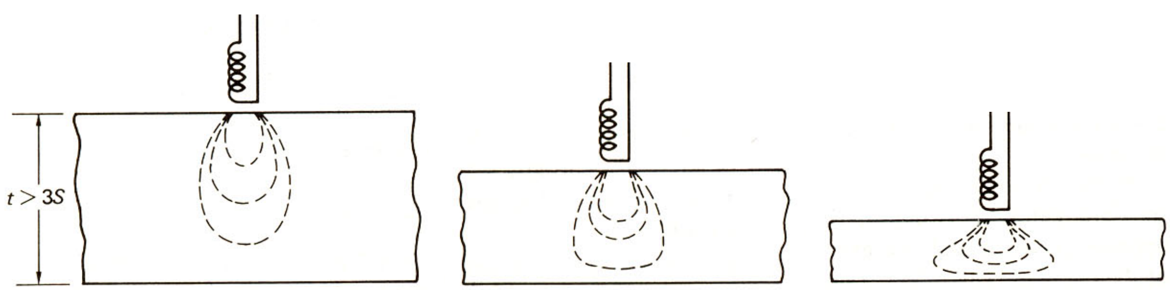


Figure 3-11. Representation of distortion of eddy current field as function of specimen thickness. Source: Ref. 6; used by permission.

specimen thickness. For relatively “thin” sections, the change in coil impedance with eddy current distortion may be calibrated as a thickness indicator (if all other influences on eddy currents remain constant). For sections roughly greater than three times the standard penetration depth, the eddy currents are no longer affected by the back surfaces. The standard penetration depth as a function of frequency is shown for selected materials in Figure 3-12.

Cracks and other sharp discontinuities in a material are typically indicated by the abrupt displacement of a vector point or spot on an oscilloscope display screen. The position of the spot represents the magnitude and phase relationship of the resistive and reactive components of the coil impedance. As the coil impedance changes with proximity to the surface (lift-off distance), proximity to the material edge (edge effects), or changes in other material properties, the position of the spot will trace a well-defined, systematic trajectory across the scope screen. With the appropriate selection of excitation frequency and coil design, flaw-related signal changes can be distinguished from non-flaw-induced changes (usually by displacement direction). The unique trace of the vector point on the screen caused by a specific type of flaw, material conductivity, lift-off distance, or other characteristics can be calibrated with the aid of appropriately fabricated material standards. Examples of these types of displays are shown in Figure 3-13.

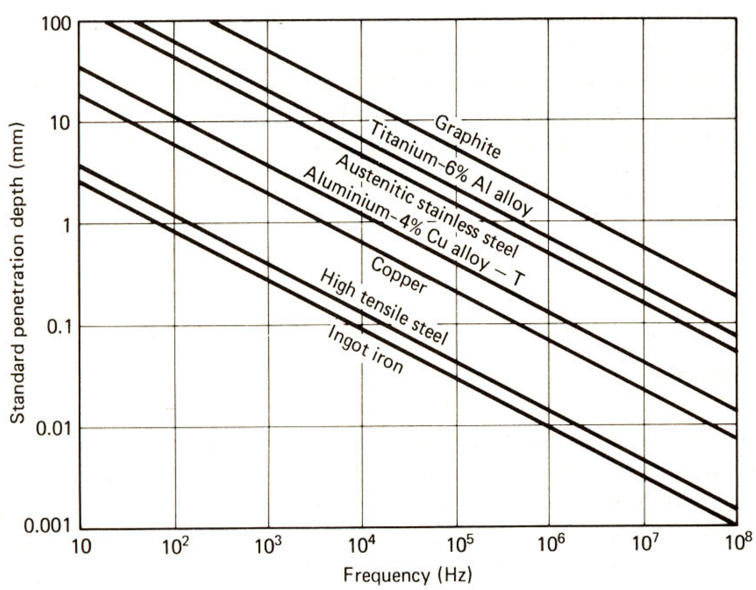


Figure 3-12. Standard penetration depth as function of frequency for selected materials. Source: Ref. 6; used by permission.

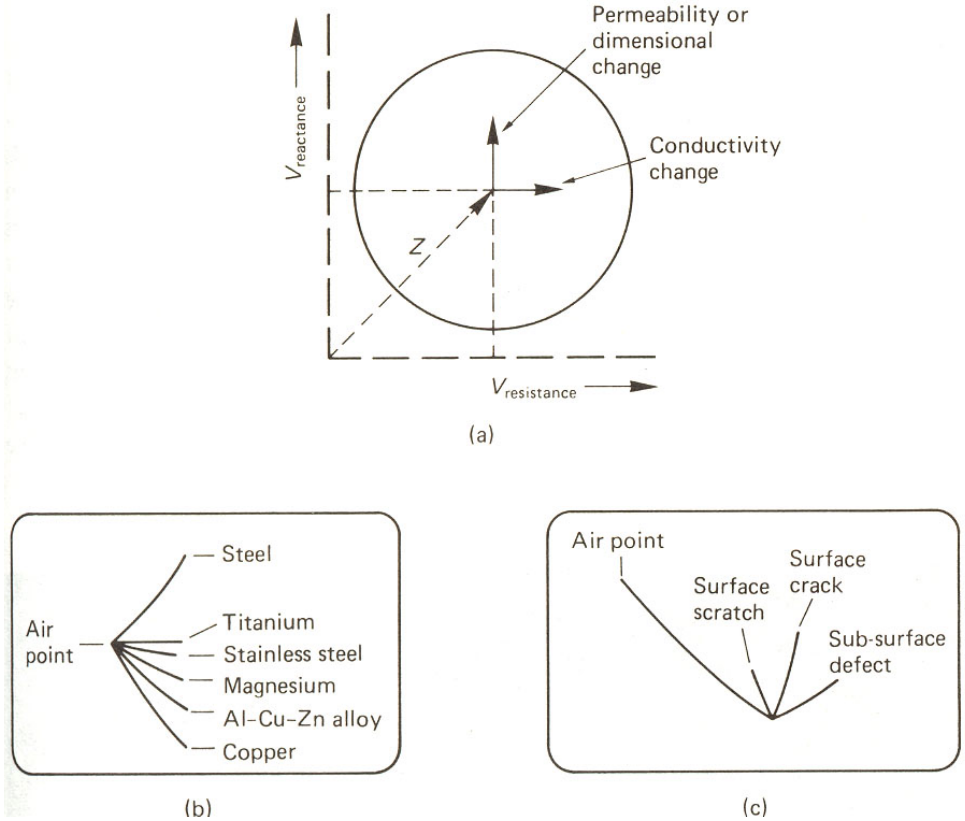


Figure 3-13. Vector point representation of coil impedance changes in eddy current inspection. (a) Impedance plane display on oscilloscope. (b) Vector point traces showing conductivity response. (c) Point traces for defect indications. Source: Ref. 6; used by permission.

3.3.3 Advantages and Disadvantages

The general advantages of eddy current inspection as compared to other NDE methods include:

- Sensitive to very fine surface and subsurface flaws, cracks, defects.
- Can be performed without surface contact.
- Can be used to assess thickness, conductivity, microstructural changes.
- Can inspect "beneath" nonmetallic surface coatings and overlays.
- Portable, adaptable to field use.

Disadvantages include:

- Single-point measurement. Probe must scan or raster to cover surface area.
- Inspection applicable only to electrically conducting materials (metals, alloys, graphite composites).

- Limited depth penetration. Skin effect (lower frequency increases penetration depth but with less sensitivity to flaws).
- Sensitivity to edge effects. Inspection must exclude regions near edges.
- Defect-related signals must be distinguished from signals caused by other material characteristic changes.

3.3.4 Applications to TPS Configurations

Because eddy current techniques are based on electromagnetic induction, they offer some capability, in principle, for the inspection of a metallic structure covered by, or buried beneath, a nonmetallic coating. The induction of eddy current is primarily a function of the target material's electrical conductivity, magnetic permeability, and proximity. Since no force or electrical signals are directly conducted from the sensor to the target, an air gap, or intervening layer of nonconductive material may be imposed between the probe coil and the surface. Typically, the eddy current lift-off response (sensitivity to proximity of the test surface) is useful for calibrating the thickness of paint, anodized coatings, or other thin layers. If the uniformity of the coating layer is not a strong variable, eddy current detection for hidden cracks in the substrate, beneath the coating, remains viable. As the coating thickness increases, however, the sensitivity of the eddy current response to substrate flaws will diminish. Several operational parameters may be tailored to optimize the response with increasing lift-off. The use of lower frequencies is the most direct approach. Probe design with effective coil shielding can shape the magnetic flux field for optimum directionality. Although it is difficult to ascribe absolute limits on crack detection sensitivity beneath coating layers for a generic material system, the potential for developing eddy current-based NDE techniques to specific RLV TPS configurations is promising.

3.4 Electromagnetic Acoustic Transducer (EMAT) Techniques

Electromagnetic acoustic transducer, or EMAT, techniques combine the electromagnetic induction of eddy currents with the generation and propagation of ultrasonic acoustic waves for the inspection of flaws in electrically conductive materials. Typically, a discussion of EMAT techniques is encountered as a subtopic in ultrasonic inspection since flaw detection relies on the reflection or attenuation of ultrasound in the material. EMAT transducers incorporate an RF coil for excitation of eddy currents and a permanent magnet (or electromagnet) to create a steady magnetic field within the material. The eddy currents induced near the surface interact with the magnetic field to produce an oscillating (or pulsed) Lorentz force normal to both fields. These forces propagate pressure waves into the part that are in sympathy with the RF frequency of the coil (thus, ultrasound). Reflected from internal flaws, the ultrasound, in turn, interacts with the magnetic field to induce current in the receiver coil. In ferromagnetic materials, similar (but relatively stronger) processes occur through magnetostrictive coupling.

EMATs offer the advantages of non-contact inspection like conventional eddy current inspection, with the penetrating depth of ultrasound propagation. The drawbacks are that the efficiency of ultrasound injection is lower for EMATs than for conventional piezoelectric transducers, and the approach is limited to the inspection of electrically conducting materials (or materials with a conducting surface layer). EMAT transducers are frequently used in applications where conventional acoustic coupling is difficult or inconsistent, or when rough or contamination-sensitive surfaces prohibit the use of conventional ultrasonic transducers. Other situations may include the inspection of moving parts, rapid scan rates, and inspection of surfaces at elevated temperature (often applied in weld processing). One key aspect of EMAT technology is that both the magnetic field component and the induced eddy currents can be configured in a multitude of orientations, allowing the generation of acoustic modes that are not easily produced by piezoelectric transducers. These alternate acoustic modes (horizontally polarized shear waves, for example) are useful in material property studies and for flaw detection schemes.

3.4.1 Equipment

The primary components required for electromagnetic-acoustic testing are similar to those used in conventional eddy current testing with the exception of the design of the transducer/probe element. Commercial EMAT systems range from very robust field equipment intended for industrial site applications to laboratory-scale material diagnostics instrumentation. Figure 3-14 shows an example of a high-temperature inspection unit used to assess metal loss in piping or vessels due to corrosion or erosion. In this example, the coil/magnet search probe can monitor wall thickness at surfaces heated to temperatures as high as 1,300ºF. Typically, the RF current generator, signal conditioners, and amplifiers are housed as a portable unit. The response signal may be sent to an oscilloscope display unit or to a computer for digital display and storage.

3.4.2 EMAT Techniques

As in the case of eddy current inspection, when a coil carrying an alternating current is placed in proximity to a conductive material, eddy currents are induced within the material and are typically confined to a shallow depth just below the surface. In the presence of a static magnetic field, (induced by a permanent magnet or electromagnet in nonferromagnetic materials), the current experiences a Lorentz force (cross product of the two vector fields). This force acting on the lattice transmits an acoustic wave (ultrasound) that propagates through the bulk of the material until it is reflected from a boundary surface or an internal flaw. In through-transmission (front and rear surface EMATs), pitch-catch (two surface EMATS), or pulse-echo (single EMAT with send and receive coils) modes, the propagating acoustic pulse is ultimately detected as an induced current in the

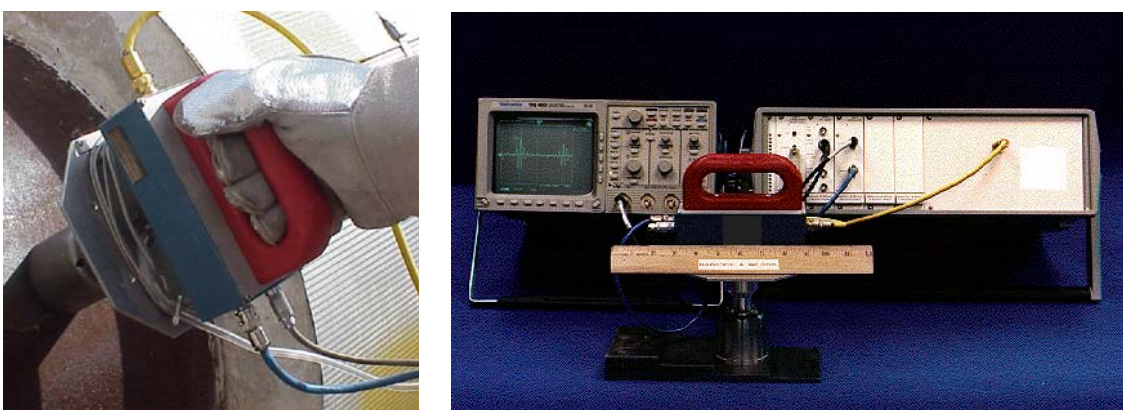


Figure 3-14. EMAT inspection of steel pipe corrosion at elevated temperature (left). Typical equipment package for EMAT inspection (right). Source: BWX Technologies, Inc.; used by permission.

receiving coil due to the motion of local charge carriers within the static magnetic field. In ferromagnetic materials, even stronger forces are derived due to magnetostrictive coupling between the magnetic field and charge carriers. Figure 3-15 shows a schematic diagram of one EMAT configuration for exciting polarized longitudinal waves propagating normal to the material surface. The resulting acoustic wave would be identical to those generated by a conventional ultrasonic testing (UT) piezoelectric transducer in direct contact with the test surface.

Other EMAT designs manipulate the orientations of the magnetic poles and coil direction to achieve other desirable acoustic modes. One example is illustrated in Figure 3-16 for the generation of plane-polarized shear waves. Such a mode is not easily achieved with piezo transducers and is attractive for properties studies in anisotropic materials.

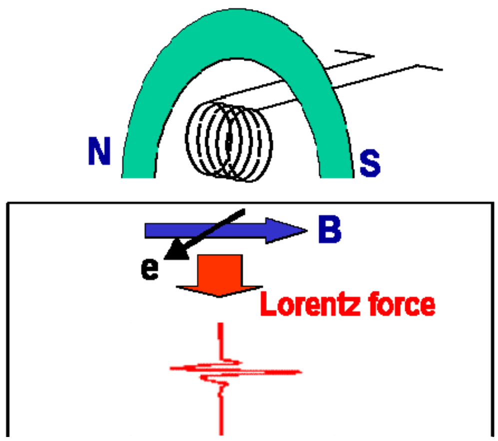


Figure 3-15. EMAT schematic for launching longitudinal acoustic waves.

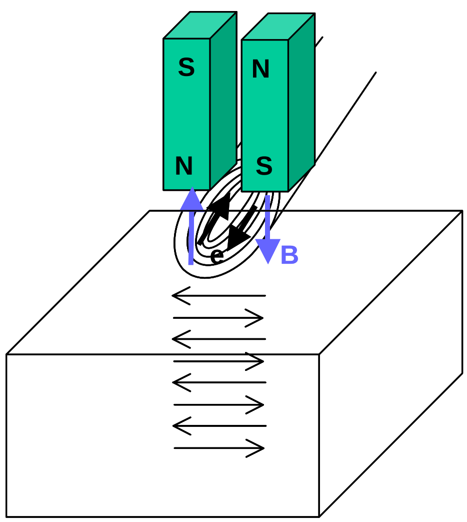


Figure 3-16. EMAT arrangement for generation of plane polarized shear waves in a material.

Bandwidths for practical EMAT designs are relatively narrow (specific in acoustic frequency) and require strong magnetic fields and large currents to produce ultrasound that is often weaker than that produced by piezoelectric transducers. Rare-earth-containing materials such as samarium-cobalt and neodymium-iron-boron are often used to produce sufficiently strong magnetic fields, which can also be generated by pulsed electromagnets. EMAT approaches for generating and detecting ultrasound in electrically nonconductive materials (glass-fiber composites) have been demonstrated with the application of thin conductive films to the test piece surface. The efficiency with which the electromagnetic coupling can be supported as a function of distance from the target material, or through the thickness of an intervening material layer (such as thermal insulation), is difficult to assess without specific EMAT design and target material properties.

3.4.3 Advantages and Disadvantages

The general advantages of EMAT inspection as compared to other NDE methods include:

- Inspection can be performed without acoustic couplant or direct surface contact. This also allows high rates of scanning and inspection of hot surfaces.
- Can inspect "beneath" nonmetallic surface coatings, overlays, and thermal insulation.
- Detects flaws by the generation and detection of ultrasonic acoustic waves. Penetration depths greater than eddy current inspection.
- Can generate acoustic modes not achievable by conventional UT.
- Portable, adaptable to field use.

Disadvantages include:

- Single-point measurement. Probe must scan or raster to cover surface area.
- Inspection applicable only to electrically conducting materials (metals, alloys, graphite composites) or systems with conducting layers.
- Due to weaker acoustic signal, flaw detection sensitivity typically lower than conventional UT.

3.4.4 Applications to TPS Configurations

Electromagnetic-acoustic technology has been developed principally for applications where non-contact or cover layer configurations have prohibited conventional ultrasonic inspection techniques. In the case of a launch vehicle, if the inspection of critical structural elements can be accomplished by ultrasound (for example, screening for cracks in an alloy skin or for delaminations in a graphite-epoxy composite shell), then EMAT technology may offer an approach for accomplishing similar inspections beneath a TPS cover layer. The injection and detection of ultrasound through the thickness of the structural element, or the propagation of surface waves throughout the structure/TPS interface, may provide a baseline map of the "good" or pre-flight condition with which to contrast post-flight inspection results. However, if ultrasound is not well suited to the inspection, due to poor sound propagation in a particular composite for instance, then EMATs will offer no distinct advantage. While existing "off-the-shelf" EMAT inspection units are suitable for a range of applications, the technology is very amenable to the development of custom transducer designs for specific and challenging applications. As typical in most critical development processes, selection of the appropriate NDE method will necessarily require direct evaluation of the technique on appropriately fabricated, representative material specimens.

3.5 Microwave Inspection

Microwaves are a form of electromagnetic radiation that occupy a portion of the electromagnetic spectrum corresponding to frequencies from approximately 300 MHz to about 300 GHz. This is radiation of wavelengths between 1 meter and 1 millimeter in free space, although the transition between shorter (infrared radiation) and longer (radio waves) wavelengths is not precise. The effects microwaves have on a material are based upon how the electric and magnetic fields of the radiation interact with the material's electrical conductivity, permittivity, and magnetic permeability. Microwaves can penetrate most nonmetallic structures (dielectrics) to varying degrees, but are strongly reflected or re-radiated by metals (good conductors). Like light, microwaves travel in straight lines until reflected, refracted, diffracted, or scattered. The basis for their use in NDE applications is analogous to the use of other forms of directed energy. As microwaves penetrate the volume of a workpiece or coating, they scatter or reflect from internal structures and flaws. When an incident wave is altered by an internal feature, the change in energy is detected and used to assess or map the condition of the target material. These techniques have been used for thickness gauging and surface crack detection in both metals and non-metals, detection of metal corrosion beneath surface coatings, and detection of cracks, voids, and delaminations in dielectric materials (plastics, composites, and insulators). The field of microwave NDE is still relatively new; however, for certain types of material systems, it offers a regime of interaction not available with other inspection techniques.

3.5.1 Equipment

Microwaves may be generated by various types of vacuum tube and solid-state devices, each generating a particular range of microwave frequencies at characteristic power levels and operating efficiencies. For most NDE applications, frequencies in the vicinity of 10 GHz (X-band) are used with modest power levels in the milliwatt regime. The components used to convey the microwave energy from the generator to the workpiece are typically a network of rectangular, hollow metal waveguides that confine the EM wave. The dimensions of the waveguide are governed by the centimeter-sized wavelength of the propagating wave. The waveguide in turn is coupled to a metal horn or antenna that can radiate or receive microwave radiation to and from the target surface. The collected microwave energy is often measured using semiconductor diodes that generate a voltage proportional to the microwave power, or with discrete phase-sensitive detector devices. The signals from an inspection arrangement are often the magnitude, phase change, frequency shift, or spectral content of the received energy, displayed on an oscilloscope screen or other recording device. Typically, microwave apparatus can be dedicated to materials studies in laboratory installations, or low-power versions can be made portable for field inspection applications.

3.5.2 Microwave Inspection Techniques

Microwave-based NDE approaches typically involve methods that can be categorized as reflection- (single-sided) or transmission-based (doubled-sided) techniques, using either fixed or swept frequencies, and either continuous-wave or pulse modulated radiation. The basis for all techniques is fundamentally the same: changes in the input reference energy caused by the interaction of the radiation with the material (at the interface and within the volume) are quantified and correlated with specific qualities of the material (changes in properties, composition, structure, size, presence of defects, etc). In many respects, the general approach for inspection is not very different from that used in ultrasonic testing. The differences lie in the how electromagnetic radiation interacts with material properties as opposed to the mechanical wave propagation of acoustic pulses. Materials highly attenuative to acoustic energy are often readily penetrated by microwaves. Also, since microwaves propagate through the air, no physical contact or coupling medium is required at the target surface.

Various schemes to measure the change in radiation reflected from the surface (reflectometers) have been reported. The most sensitive means of detecting changes resulting from small cracks is to monitor the standing wave produced in a resonant cavity configuration with the surface. In this arrangement, the reflected wave combines with the incident wave to produce a standing wave. The presence of a crack and its orientation influences the re-radiated wave (analogous to the effect of induced eddy currents). Microwaves are also affected during their propagation through homogeneous nonmetallic materials, primarily by the interaction of the electric field with the dielectric (molecular) properties of the material. Storage and dissipation of the electric field energy by the polarization and conduction behavior of the material are the mechanisms. Thus, chemical changes that affect the dielectric constant and/or loss tangent can be monitored by assessing the change in the refracted or transmitted microwave energy. These techniques are also used to measure specific gravity, moisture content, glass-to-resin ratio, and several other material characteristics. Discontinuities within the bulk of a dielectric material such as cracks, voids, delaminations, and inclusions reflect or scatter electromagnetic waves if their minimum dimension is larger than about one-half the wavelength of incident radiation in the material (thus, roughly about 0.5 mm).

3.5.3 Advantages and Disadvantages

The advantages of microwave inspection as compared to other NDE methods include:

- Particularly effective for penetrating dielectric materials (nonmetallics, insulators).
- Efficient coupling of radiation through the air between antenna and workpiece.
- Volumetric scanning, enabling the inspection of a volume of material extending from front to back surfaces.
- Requires no physical contact; no contamination issues.
- Can be used in both single- or double-sided configurations.
- Apparatus consists of small, rugged, solid-state components; portable for field applications.

Disadvantages include:

- Microwaves do not penetrate deeply into conductors or metals (good reflectors of microwave radiation).
- Due to scale of radiation wavelength, small flaws are difficult to resolve (on scale of 1 mm).
- Single-point measurement, must scan or raster to cover large areas.
- Relatively new NDE technology.

3.5.4 Applications to TPS Configurations

Microwave inspection offers an interesting potential for NDE of structures covered by TPS. While most thermal insulating materials fall within the category of dielectric materials penetrable by microwaves (layers of cork, coatings of high-temperature tolerant polymers, phenolics, fiber composites), it is not certain whether microwave interaction with, or reflection from, the underlying structure would be sufficient to assess the state of health of that structure. Typically, sensitive surface-crack detection schemes (e.g., for fatigue cracks in metals) are based on microwave systems that are close range, near-field designs, without intervening materials of substantial thickness. However, its application to metal corrosion under paint coatings offers a close analogy. If the underlying structure were fabricated from a resin-based composite material (with "poor conducting" graphite fibers, for instance), microwaves could possibly penetrate through the TPS and into the surface of the structure. Electromagnetic scatter by defects within the structure (cracks or delaminations) could be evaluated to assess the condition of the covered structure. While microwave NDE has shown promise for evaluation of external insulation materials on the Space Shuttle, the present experience base is too limited to fully assess its potential as a meaningful tool for the inspection of TPS-covered structures.

3.6 Thermographic Inspection

Thermography is a thermal inspection technique that involves the measurement or mapping of surface temperatures when heat flows from, to, or through a test object. The approach is well suited for the detection of subsurface flaws or voids, provided the depth of the flaw is not large compared to the overall size of the part. The basic process involves the use of a heat sensing system or thermal imaging (infrared) camera that can view the surface of a test object as it is heated (or cooled) for a brief period. The presence of subsurface flaws will affect the heat flow pattern on the surface as the heat diffuses through the object. The amount of heat required for inspection, the time required for surface thermal gradients to develop, and the resolution of subsurface defects all depend on the thermal properties of the test object and the sensitivity of the thermal imaging system employed for the inspection. The technique permits rapid, non-contact inspection of very large and complex surfaces and can be performed when access is limited to one side. Components often inspected by thermography include adhesively bonded panels, sandwich structures, honeycomb panels, etc., where the presence of disbonds, delaminations, or voids can be crucial to the structural integrity of a component. Since the technique relies on the resolution of surface temperature gradients for the indication of subsurface defects, deep flaws and materials with high thermal diffusivity (metals) can be difficult to inspect. However, creative heating flow configurations (steady-state to rapid flash or pulse heating) and post-inspection image analysis are continually evolving to widen the field of application.

3.6.1 Equipment

The range of thermal inspection techniques covers both thermally active test objects, where the inspection relies on self-generated heat flow to detect anomalous behavior (electronic circuit board components, heating ducts, or active pipelines), and thermally passive test objects, where an external source of heat flow is required (laminate structures). In both cases, the heat sensing device is typically an infrared imaging camera. For most thermographic inspection applications, portable, high spatial resolution, high temperature sensitivity IR imaging systems are used that can digitally capture and download high-frame-rate image data files. Dedicated software is available to process, enhance, and display the time-evolved thermal patterns that contain the flaw signatures. Depending on material diffusivity and flaw depth, the flaw images may develop over a timeframe of milliseconds to several seconds. For thermally active test objects, alternate temperature-sensing approaches may be used, such as temperature-sensitive contact coatings, heat-sensitive paints, or liquid-crystal compounds. These methods, however, do not have the advantage of camera-based "non-contact" inspection.

For the inspection of thermally passive components, the only remaining equipment required is a heat source. Effective sources include: hot air guns, hot water spray, heat lamps, or flash lamps. Two essential concerns regarding the use of external heat flow are: (1) the inspection region must be heated (or cooled) uniformly, and (2) the heating period must be commensurate with the material diffusivity and flaw depth. For relatively deep flaws in a low-conductivity laminate structure, a quantity of heat may be imposed by scanning over several seconds with a quartz lamp. As the heat diffuses to the depth of the flaw (in a rear bondline, for instance), the local surface temperature will begin to show the influence of the discontinuity in conduction caused by the flaw, and an optimum "hot spot" may develop on the order of a few seconds after heating. For near-surface flaws, or if the material is a good thermal conductor, pulsed or flash lamp heating may be used, often triggered and synchronized with automated data collection, to discriminate flaw features that develop on the order of milliseconds after heating. Most methods of heating and sensing are readily adaptable to field use and can be scaled for highly detailed, fine-resolution inspection, as well as wide-field-of-view detection on large surfaces. Figure 3-17 illustrates the basic setup for performing thermographic inspection on thermally passive targets.

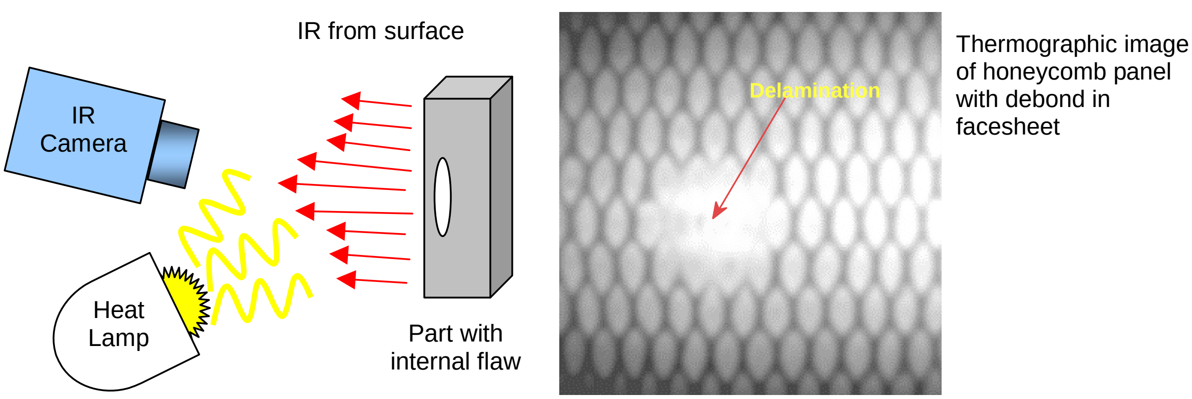


Figure 3-17. Basic set-up for performing thermographic inspection on thermally passive targets.

3.6.2 Thermography Inspection Techniques

In many cases, thermography inspections may be performed by simply using an IR sensing camera, a hand-held, radiant heat lamp, and a videotape recorder for storing the time-evolved IR imagery data. As with other NDE inspection techniques, material “defect” reference standards are often created to replicate the anticipated defect sizes and locations that would be relevant to a particular inspection. Typically, the defect standards can provide a reasonably good empirical assessment as to necessary control of the application of heat, minimum spatial resolution, and temporal response time needed for thermographic inspection. For the inspection of thermally active test objects, the thermal imaging system (IR camera) is the primary inspection tool. A well characterized control or nominal test sample is also required, against which subtle thermal anomalies can be assessed, as in the examples in Figures 3-18 and 3-19.

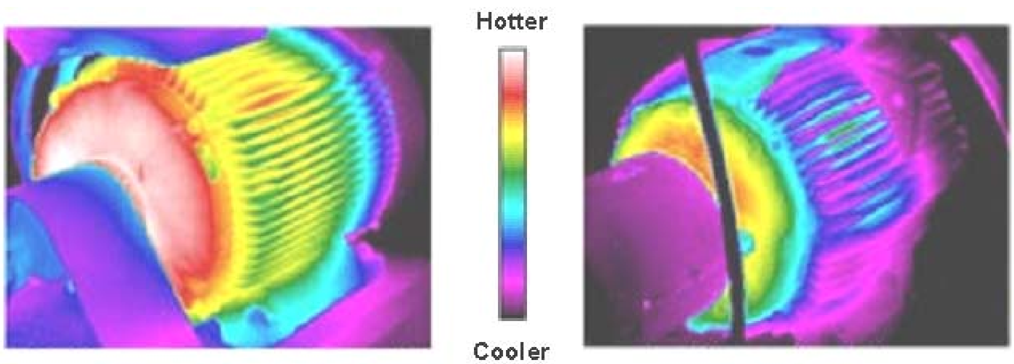


Figure 3-18. Infrared images of two motors, showing marked temperature rise on motor on left. Source: Academy of Infrared Training, Inc.

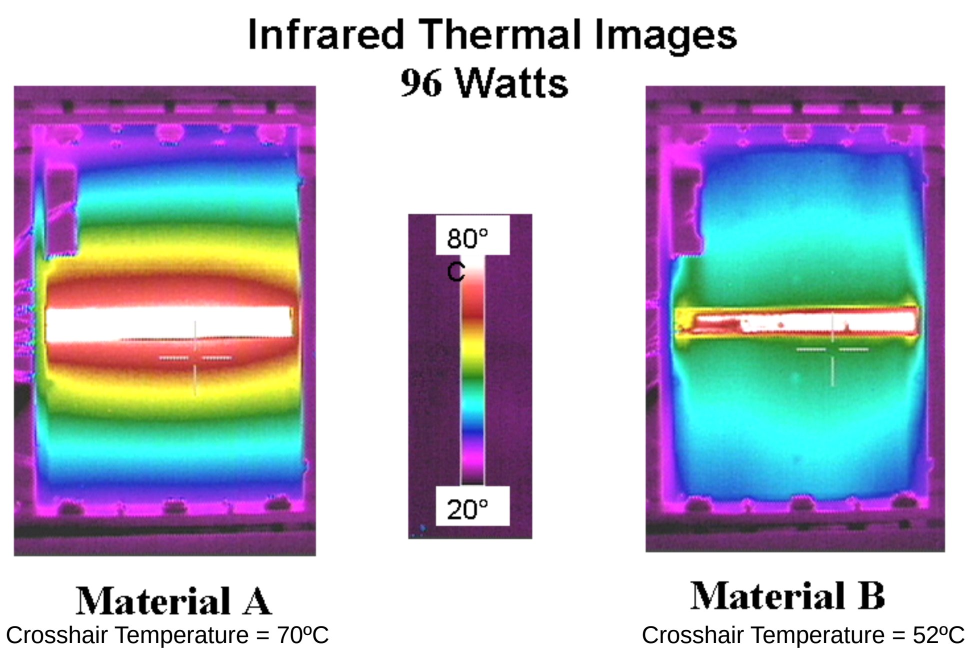


Figure 3-19. Infrared images showing temperature distributions in two thermal diffuser components operated at the same power level.

As an inspection process, thermography offers a considerably wide range of detection sensitivity, particularly in its application to thermally passive test objects, where the surface is intentionally heated or cooled to induce a thermal gradient to reveal internal flaws. Although the application of heat can be accomplished in a variety of ways, one method that offers a high degree of consistency and is adaptable to high-rate, high-volume inspection is “pulse” or flash heating. A system of high-power xenon flash lamp units, similar to that used in commercial photography, is typically used in thermography to provide uniform, large-area heating in a very short period (heating time on the order of a few milliseconds). Flash heating is particularly suited to the detection of adhesive voids in lightweight aerospace components such as solar cells and optical solar reflector tiles where continuity of bondline is critical to the thermal stability of the component (Figure 3-20). Similarly, the inspection of bondline effectiveness at embedded heat pipes, heaters, and thermal radiators in spacecraft systems by thermography is ideal for assessing thermal flow performance. In conjunction with the use of pulse heating, high-frame-rate image capture (up to 500 fps) by computer allows the post-heating assessment of highly transient thermal events. Methods involving multiple frame averaging, subtraction, and other image processing techniques are also exploited to reveal subtle thermal detail.

A variation of the typical surface flash heating configuration is “rear side” or through transmission thermography. In this case, an unbond or flaw interrupts the flow of heat to the camera side of the test object, thus appearing “cooler” than the surrounding material. One example of this method is shown in Figure 3-21 for a case where IR transparency of a Kevlar facesheet allowed the thickness of the Kevlar-to-aluminum bond “fillet” to be directly viewed by an IR camera after pulse heating the rear facesheet. Variations in fillet thickness were used to identify honeycomb panels that were not processed correctly.

Further advancements in detection capability with thermography have enabled reassessment of image data through the creation of a set of mathematical equations that model the time response of each pixel in the raw dataset. This “reconstruction” process can significantly improve identification of subsurface flaws without the use of a reference by greatly reducing signal noise and enhancing the contrast between defect locations and defect-free areas. An example of such reconstructed images is show in Figure 3-22.

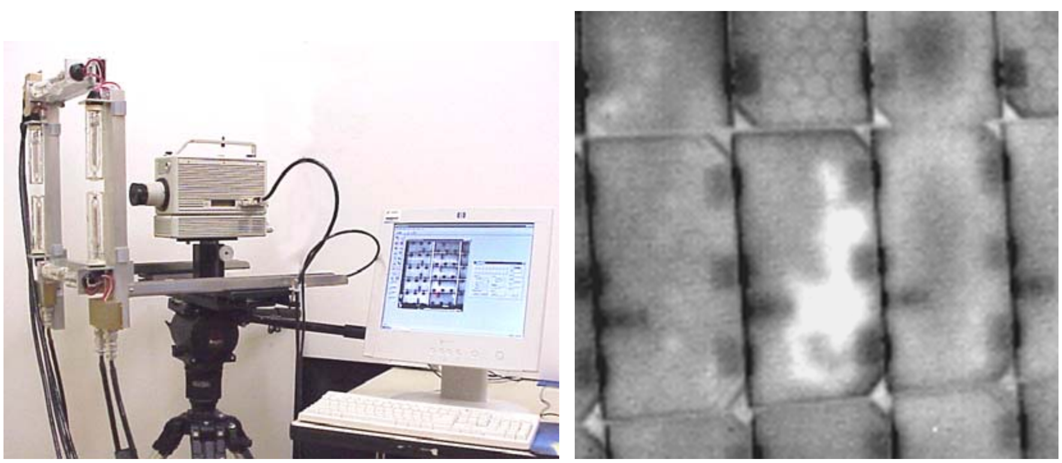


Figure 3-20. Flash lamp, IR camera, and computer set-up: Thermography image of an adhesive void in a solar cell array.

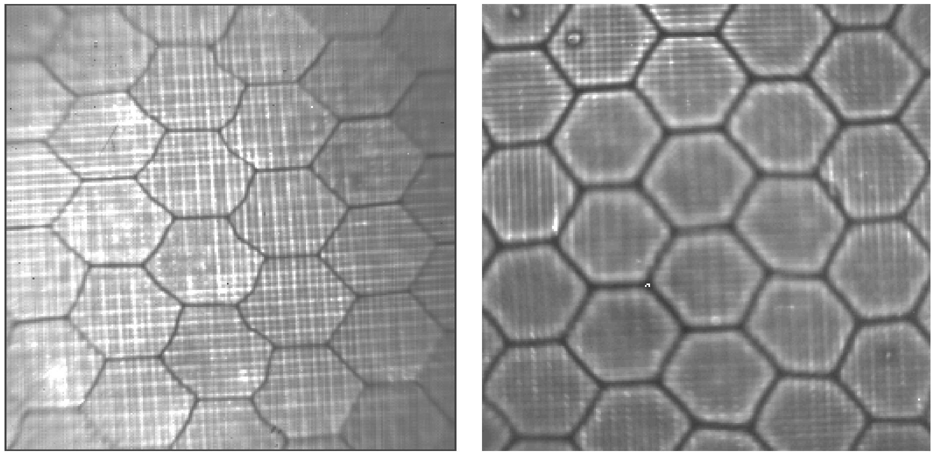


Figure 3-21. IR images of aluminum honeycomb adhesive fillet using "through transmission" thermography mode. Thinner bond fillet was result of poor adhesive processing.

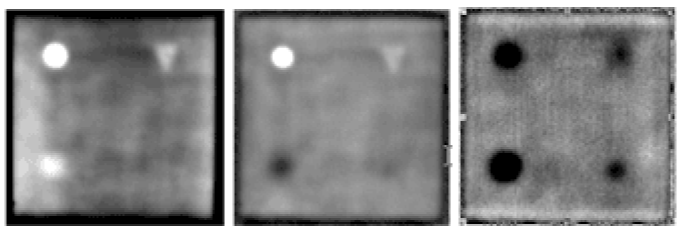


Figure 3-22. Pulsed thermography results for a C/SiC specimen with seeded flaws. At left is the raw thermal image. Center and right are the 1^{st} and 2^{nd} derivatives generated from the reconstructed thermal data, revealing indications from the deepest flaw. Photographs courtesy of NASA; used by permission.

3.6.3 Advantages and Disadvantages

The general advantages of thermography as compared to other NDE methods include:

- Volumetric and "wide-field" coverage. Two-dimensional area is instantaneously inspected with a specific depth sensitivity.
- Non-contact inspection process. Well suited to fragile, contamination-sensitive surfaces.
- Rapid, high-rate inspection. Raw data can be captured quickly, stored, and processed at a later time.
- Large area coverage. Depending on minimum flaw size resolution, wide camera field-of-view may be employed.
- Single- and two-sided access techniques available.
- Portability, adaptable for field use.

Disadvantages include:

- Thermal properties must be amenable to the technique. Good thermal conductors difficult to inspect. Good insulators also difficult to inspect.
- Limits to penetrating power. Very deep flaws can be difficult to resolve.
- Equipment cost relatively high. High-quality IR imaging cameras are expensive. Dedicated image processing software is required.
- Portable multi-element systems (camera, lamps, computer) are bulky and inconvenient to transport.

3.6.4 Applications to TPS Configurations

Thermography is an NDE approach that may be applicable to the types of material systems used in advanced TPSs. Since the technique relies on the propagation of heat to reveal subsurface defects, very good thermal insulating materials typically are not easily inspected by thermography. Often, however, TPSs rely on diverse systems of coatings and protective layers over bulk insulators to achieve reentry effectiveness. Monitoring the health of such protective layers may be critical in future TPS designs, and thermography can be a vital tool.

One example is the reinforced carbon/carbon composite structure forming the leading edges of the current Space Shuttle fleet. The carbon/carbon composite is protected from oxidation during reentry by a layer of silicon carbide (SiC). Due to thermal expansion mismatch, however, a fine network of cracks eventually forms within the SiC layer. To fill these cracks, a sodium silicate-based glass, that becomes fluid at high temperature, is used to coat the silicon carbide layer. This layered system has been proven effective through multiple reentry heating cycles. Routine NDE on this and other TPS elements on the Shuttle have relied primarily on careful and exhaustive visual inspection techniques. One mode of TPS degradation is due to formation of small pinholes (approx. 0.1 mm dia.) in this multi-component system. The pinholes are caused by weathering of paint on the launch structure, which leads to deposits of zinc-containing paint flakes on the wing leading edge. The zinc oxide reacts vigorously with the glass coating, leading to the pinhole formation. If the glass cannot effectively seal these pinholes, oxidation of the carbon/carbon can lead to progressive material loss beneath the SiC layer, weakening the structure.

Thermographic images of a specimen of reentry-exposed Shuttle leading edge are shown in Figure 3-23. The image on the left is a photograph of the specimen with a series of flat-bottom holes of various depth and diameters that serves as a flaw reference. The IR images of the opposite face are taken at progressively longer times after flash heating (the IR images have been reversed to aid coordinating hot spots with holes in the photograph). While the smallest and deepest flaws are not resolved, thermography displays significant detail of internal void structure. Particularly interesting is the clarity of the surface crack network on the SiC layer.

Other interesting features in the thermographic survey of the Shuttle leading edge are regions that have experienced some extent of material repair. Figure 3-24 shows a poorly bonded or lifted surface adjacent to a missing patch of SiC. Hidden carbon/carbon material loss beneath the SiC layer could be resolved in much the same manner.

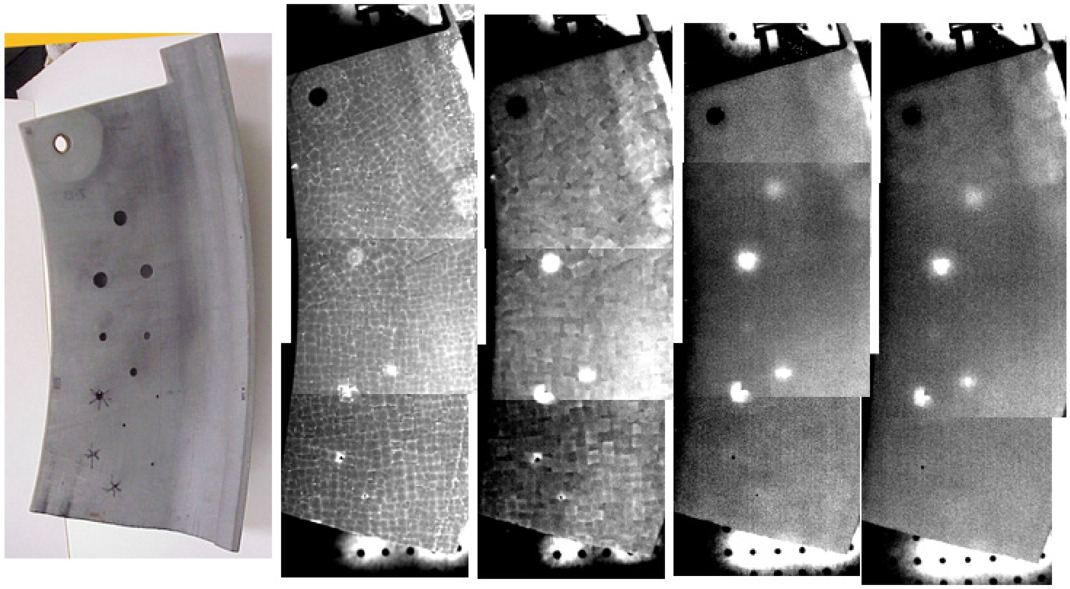


Figure 3-23. Thermographic images of reentry-exposed Shuttle leading edge.

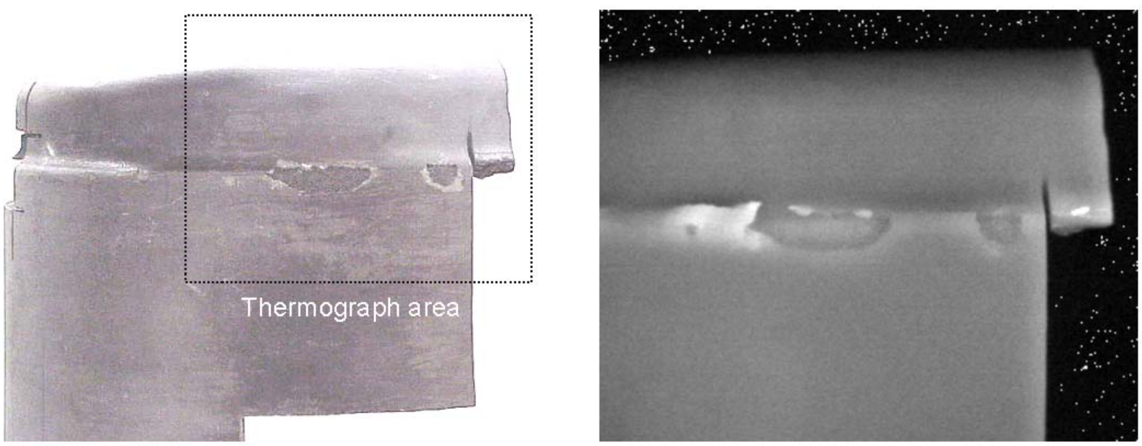


Figure 3-24. Thermography of repaired area on Shuttle leading edge.

These examples of thermography applied to the Shuttle TPS may be relevant to NDE of alternate multi-component material systems proposed for advanced TPS tiles. For the case of NDE inspection of structures beneath TPS, where the inspection process must penetrate through the TPS, application of thermography would be challenging. Thermography cannot be employed where standoffs or air gaps intervene in the path to the test structure.

3.7 Radiographic Inspection

The use of very short wavelength, penetrating electromagnetic radiation, namely X-rays or γ-rays (gamma radiation), as well as neutron radiation, to image the details of internal structures is one of the most familiar methods of NDE. Radiography is capable of distinguishing most internal features in a component or structure that have a significant differences in radiation absorption due to changes in material thickness or density. For inspection of internal flaws, the best results are obtained when the defect has an appreciable thickness in a direction parallel to the radiation beam. The most common types of defects revealed by X-ray inspection are those that have measurable thickness in all directions, such as porosity and other voids, and material inclusions. Planar discontinuities, however, such as cracks or delaminations, can be difficult to detect unless they are favorably orientated with respect to the beam. In general, features that exhibit a 1% or more difference in absorption compared to the surrounding material can be detected by radiography.

Radiographic inspection may be performed on most metallic and nonmetallic components; however, very high- and very low-density materials may pose difficulties for use of X-rays and γ-rays. Neutron radiography, on the other hand, is excellent for imaging targets of both light and heavy elements. Radiography is extensively used on castings and weldments, particularly where there is a critical need to ensure a defect-free structure (e.g., high-pressure boiler and turbine components). High-resolution, real-time X-ray imagery is often used to ensure proper assembly of sealed components and to inspect semiconductor devices for cracked or broken wires, foreign material, or misaligned elements.

3.7.1 Equipment

The principal elements required to perform radiographic inspection include a radiation source, the part to be evaluated, and a sensing or recording material (film or detection system). The two most common types of penetrating radiation used for inspection are X-rays and γ-rays. X-rays are produced in an electronic device (X-ray tube) in which a stream of electrons, emitted from a hot tungsten filament, are accelerated and impinged upon a target material. The collision of high-energy electrons with the target (also typically tungsten) results in the emission of X-rays. Gamma rays are generated during the radioactive decay of either naturally occurring or man-made unstable isotopes. Two commonly used radioactive isotopes are iridium-192 and cobalt-60. In all respects other than their origin, X-rays and γ-rays are identical.

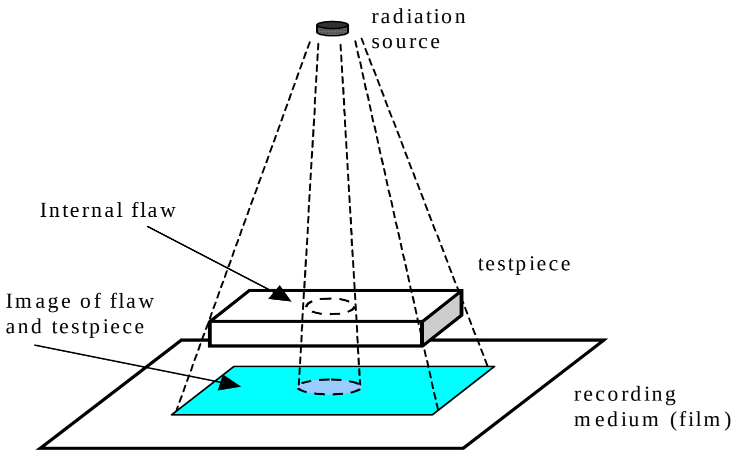
Typically, the radiation source is positioned on one side of the testpiece, while on the other side, a recording medium (usually film) is positioned to receive the unabsorbed radiation. After the film is processed in a manner similar to processes for photographic film, it provides a permanent image of the intensity variation or contrast resulting from variation in radiation absorption caused, in turn, by internal discontinuities. Low-density features, such as voids, result in higher local radiation exposure of the film (dark regions on the developed film). The image is much like a shadow cast by a beam of light through a partially opaque object.

Testpiece identification markers and penetrameters are included in each radiograph. Penetrameters, or image quality indicators, are materials of specific size and shape (often small wires) that aid in the interpretation of the radiograph by ensuring that the desired sensitivity, definition, and contrast have been achieved in the developed image. While details of subtle flaw structure may be revealed, the depth of a flaw within the testpiece volume cannot be determined with a single radiograph. Multiple-angle exposures or other techniques, such as real-time imaging or computed tomography (CT), are required for complete 3-dimensional assessment. Real-time imaging systems may use a variety of image conversion techniques to view results while the testpiece is in motion with respect to the radiation source. Fluorescent screens in combination with image intensifiers and television cameras provide a means to view the unabsorbed radiation as the testpiece is exposed. Scanning electronic detector arrays are also used to receive and digitize the transmitted radiation to produce near-real-time image displays (digital radiography). Despite the immediacy and the advantage of testpiece manipulation, the sensitivity and resolution of real-time systems are usually not as good as those typically achieved with simpler film-based radiography. While most radiographic inspections are performed in dedicated radiographic laboratories designed with precautions to avoid personnel exposure to radiation, field inspections, using portable radiation sources, are performed quite readily with appropriate radiation shielding and personnel safety protection.

3.7.2 Radiographic Techniques

Most radiographic techniques are based on the following fundamental principles: The object to be examined is placed in the path of radiation from the source (X- or γ-radiation). The recording medium is placed close to the object being examined on the opposite side from the source. Unlike visible light, the radiation cannot be focused, but typically emanates from the source as a conical beam. Figure 3-25 shows a schematic depiction of this arrangement.

As the radiation penetrates the material, it will be attenuated to some degree by various atomic interaction processes. The radiation that emerges from the material will produce a latent image on the recording medium. The presence of internal flaws that vary in absorptive power from the bulk material will change the amount of local radiation exiting the part. Thus, a flaw will be represented by a shadow of lesser or greater density than the surrounding material. The practical limit in detecting and resolving small features of varying contrast in the recording medium is a complex function of the penetrating power of the radiation (spectral intensity, in turn, a function of X-ray tube voltage), material absorption (composition, density), part thickness, and recording media sensitivity. As mention above, the use of calibrating elements within the radiographic image (e.g., penetrameters) is vital to assessing that the appropriate sensitivity to flaw contrast is achieved.



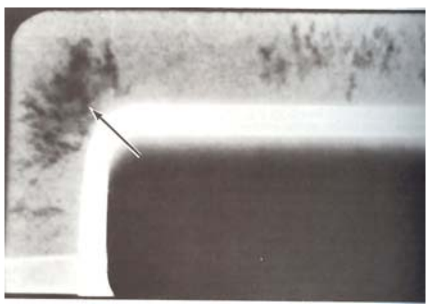


Figure 3-25. Schematic depiction of basic radiographic inspection setup. Right: Radiograph of aluminum casting with significant shrinkage porosity (arrow). Photograph source: Ref. 7; used by permission.

A number of complex interactions and radiation scattering phenomena can complicate the interpretation of the radiographic image. The most important ones are mentioned here. Because the radiation propagates in straight lines from a small but finite source, the dimensions of shadow features are enlarged with distance from the object. This can produce an overlap of contrast for complex parts with varying thickness. The quality of the image can be affected by geometrical unsharpness due to the finite size (or closeness) of the radiation source, causing penumbra effects. (Very small focal spot sources play an important role in real-time, high-definition systems). Unsharpness also arises from internal radiation scatter within the testpiece as well as backscatter from surrounding setup hardware. Each inspection situation demands careful review of appropriate radiation energies, filtering screens, and setup configurations in order to optimize radiographic definition. Ultimately, a comprehensive understanding of how various types of flaw orientations in a specific workpiece can be optimally imaged is essential for successful inspection. The difficulties of imaging planar defects such as cracks are illustrated in Figure 3-26 along with a schematic representation of tangential inspection of a cylindrical workpiece with a circumferential flaw (delamination) (Figure 3-27).

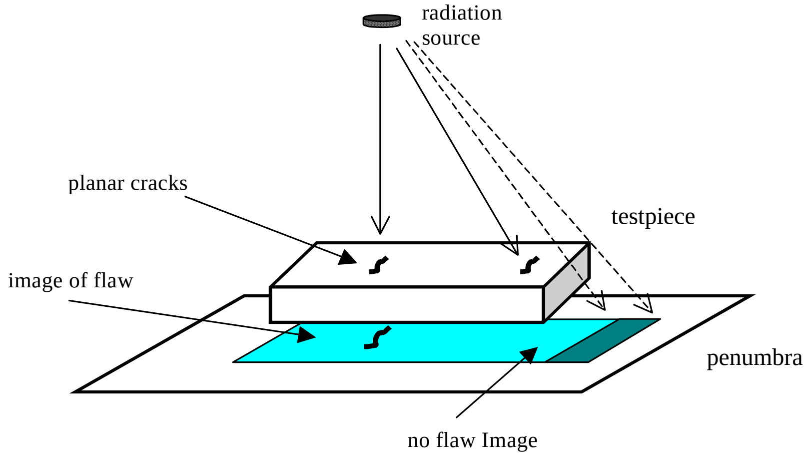


Figure 3-26. Orientation of flaws for optimum density change and image contrast.

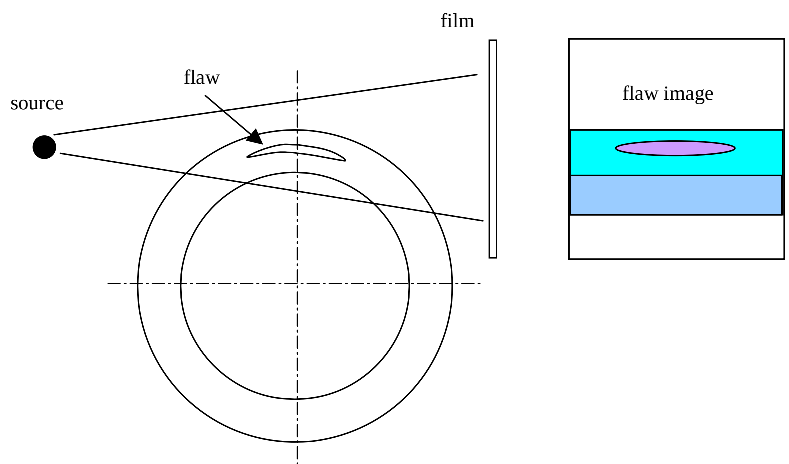


Figure 3-27. Tangential radiographic inspection of cylindrical segment for maximum contrast of circumferential flaw.

The same general principles of shadow formation, attenuation with thickness, and other geometrical effects that apply to X-ray and γ-radiation radiography also apply to the use of neutron radiation. With no electrical charge, neutrons interact primarily with the target's atomic nuclei (neutron scatter, or capture). Because of this, some elements and isotopes display much greater attenuation, making it possible to detect certain low- and mid-atomic number elements (e.g., hydrogen, boron, cadmium) even when they are present with high atomic number elements (e.g., iron, lead). The ability to produce excellent resolution and high contrast images of targets composed of both low- and high-density materials is the primary advantage of neutron radiography. Recording a neutron image generally requires use of a special screen or foil that produces a secondary emission, which is then exposed to the film. This transfer process in film exposure makes it possible to inspect radioactive specimens (nuclear fuel components) that would otherwise cause fogging with conventional radiography. Sources for neutrons include radioisotopes (transportable), accelerators, and nuclear reactors (fixed site). Optimum material discrimination for radiographic inspections typically involves the use of low-energy, thermal neutrons (0.01 to 0.5 eV).

3.7.3 Advantages and Disadvantages

Advantages of radiographic inspection as compared to other NDE methods include:

- A two-dimensional image is produced documenting the presence of the internal flaws.
- A wide range of materials may be subjected to radiographic inspection.
- Very fine void defects and internal details can be revealed.
- Real-time radiography can provide rapid assessment and location of internal features.
- Portable for field applications (film techniques).

Disadvantages include:

- More expensive than other NDE methods. Initial capital and operating costs can be high. Setup, film exposure and development can be time consuming.
- Requires dedicated expertise and experience to interpret radiographic images.
- Requires sufficient density variation. Cracks and other planar flaws are difficult to image.
- Typically applied in "through transmission" configurations; requires access to both sides.
- Flaw depth is resolvable only with multiple-angle exposures or real-time systems.
- Radiation hazard imposes personnel safety requirements.

3.7.4 Applications to TPS Configurations

Because radiographic inspection methods are not necessarily limited by material selection or constraints of penetration depth, they offer the most direct means of inspecting TPS-covered or other inaccessible structural components. In fact, X-rays are used to examine the interfacial bondlines and the material integrity of multilayer systems on large solid rocket motors (including propellant, insulator, motor case, and TPS). An important consideration, however, in the application of radiography is accessibility for optimum source and film orientation in and around the desired inspection area. Typically, radiographic film would be attached to the interior surface of the structure (for weld inspection, as an example), with the radiation source on the exterior. If access to the interior is unavailable, as in the case of closed pressure vessels, radiation penetrating from the opposite side of the structure, across the diameter, may be a reasonable alternative. In cases involving the inspection of cylindrical elements (e.g., for delamination-type flaws in composite tubes), several tangential exposures across an arc segment of the circumference is the most viable approach. This is because the contrast or density change normal to a delamination is essentially zero (similar to the case of a planar crack). As the shape of the workpiece departs from the regular curvature of a cylinder, tangential shots may become less effective. Thus, another important consideration in the use of radiography is the ability to locate the radiation source/recording media for proper orientation with respect to the anticipated flaw structure. Often, radiography may be used for the acceptance of a component following an initial stage of fabrication but prior to final assembly. If a periodic inspection can be performed on disassembled components, many of the issues associated with accessibility are relieved. This may not be a viable approach in the case of large flight structures with TPS-covered areas. When evaluating the option of radiographic inspection against other methods of NDE for inspecting flight structures, the following key considerations should be addressed: optimum beam orientation, minimum flaw size resolution, and operating costs.

4. Conclusions and Recommendations

Brief descriptive summaries of selected NDE methods relevant to the inspection of aerospace structures covered by TPS have been presented. The inherent strengths and limitations of each were discussed in the context where the presence of TPS limits direct contact with the underlying structure, imposes a standoff distance, and/or blocks line-of-sight access. The goal was to acquaint the reader with the basic principles of each technique and conventional methodologies for their application. Selection of suitable NDE methods for TPS-covered structures must take into account several factors. Due to the variety of TPS materials and design configurations, and unknown inspection criteria for the covered structure (flaw size limits), no single NDE method can be regarded as the most effective approach. However, knowledge of specific TPS/structure design data and an understanding of these basic NDE concepts together enable critical evaluations of proposed inspection approaches. Although many NDE approaches currently exhibit limitations for inspecting TPS-covered structures, those methods most suited for continuing development have been identified and discussed.

5. Abbreviations and Symbols

AE	acoustic emission
AST	Office of Commercial Space Transportation
COTR	Contracting Officer's Technical Representative
C/SiC	carbon fiber reinforced, silicon carbide matrix composite material
CT	computed tomography
CW	continuous wave
deg	degree
EMAT	electromagnetic acoustic transducer
emf	electromagnetic field
eV	electron volt
FAA	Federal Aviation Administration
ft	foot
fps	frames per second
γ	gamma
GHz	gigahertz
h_f	heat of fusion
IR	infrared
kHz	kilohertz
lb	pound
LTA	low temperature ablative
MCC-1	sprayable cork ablator insulation
MHz	megahertz
MI-15	low-density filled elastomeric silicone TPS material
mm	millimeter
MSA-2	Marshall sprayable ablator
NDE	nondestructive evaluation
RF	radio frequency
RLV	reusable launch vehicle
S	standard penetration depth (eddy current)
s	second
SiC	silicon carbide
TPS	thermal protection system
UT	ultrasonic testing

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The following primary sources were drawn upon to compile the general descriptions of NDE techniques discussed in this report:

1. Ref. 6 above.

2. Ref. 7 above.

3. Cole, P. T., *The Capabilities and Limitations of NDT, Part 7 – Acoustic Emission*, The British Institute of Non-Destructive Testing, Chartwell Press Ltd, (1988).