PDHonline Course M470 (4 PDH)

Common Nondestructive Testing_NDT - Part 3

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2020

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OBS.: This is a didactic and professional handbook. It´s highly recommended downloading and printing the course content for your study, before answering the quiz questions.

1. Acoustic Emission Testing (AE):

Unlike conventional Ultrasonic testing, AE tools are designed **for monitoring acoustic emissions** produced within the material during failure or stress, rather than **only actively transmitting waves**. Part failures can be documented during multiple load cycles and form the basis for many AE inspection methods, for example, to study the **formation of cracks** during the welding process, opposed with the more familiar ultrasonic testing technique.

Some components of an airplane during flight, transducers can be mounted in an area to detect and record signals, **locating the precise area** of the formation of a crack, at the **moment it begins**, by measuring the time through the sound of different transducers. This technique is also valuable for detecting cracks forming in pressure vessels, pipelines under high pressures and estimation of corrosion in reinforced concrete structures.

With the right equipment and setup, motions on the order of picometers (10 -12 m) can be identified. Sources of AE vary from **natural events like earthquakes and rock bursts** to the initiation and **growth of cracks,** slip and dislocation movements, melting, twinning, and **phase transformations in metals**. In composites, matrix cracking and fiber breakage contribute to acoustic emissions. AE's have also been **measured and recorded** in polymers, wood, and concrete, among other materials.

Detection and analysis of AE signals can supply valuable information regarding the origin and importance of a discontinuity in a material. Because of the versatility of Acoustic Emission testing (AE), it has **many industrial applications** (e.g. assessing structural integrity, **detecting flaws, testing for leaks, or monitoring weld quality)** and is used extensively as a research tool.

1. Theory - AE Sources:

Depending on the magnitude of the stress and the properties of the material, an object may return to its original dimensions or be permanently deformed after the stress is removed. These two conditions are known as **elastic and plastic deformation**, respectively. The most **detectible acoustic emissions** take place, when a loaded material undergoes its plastic deformation or when a material is loaded at or near its yield stress.

These **atomic-scale deformations release energy** in the form of elastic waves which "can be thought of as naturally generated ultrasound" traveling through the object. When **cracks exist** in a metal, the stress levels present in front of the crack can be several times higher than the surrounding area. The AE activity will be observed when the material ahead of the crack tip undergoes plastic deformation (micro-yielding).

Two sources of fatigue cracks also cause AE's. The **first** source is **emissive particles** (e.g. nonmetallic inclusions) at the origin of the crack tip. Since these particles are less ductile than the surrounding material, they tend to break more easily when the metal is strained, resulting in an AE signal. The **second** source is the **propagation of the crack tip** that occurs through the movement of dislocations and small-scale cleavage produced by triaxial stresses.

The amount of energy released by an acoustic emission and the amplitude of the waveform are related to the magnitude and velocity of the source event. The amplitude of the emission is proportional to the velocity of crack propagation and the amount of surface area created. Large, discrete **crack jumps** will produce larger **AE signals** than cracks that propagate slowly over the same distance.

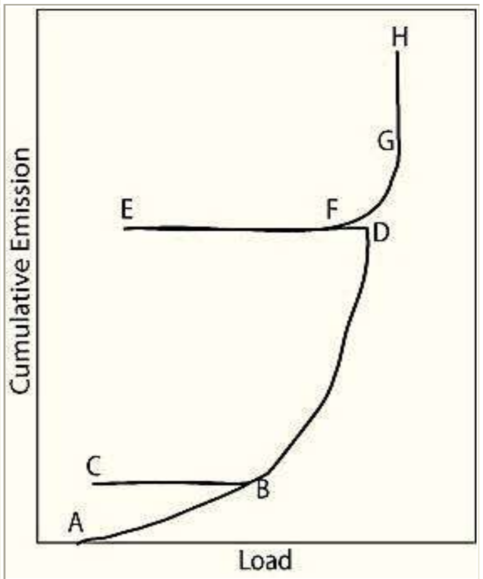
Detection, conversion and interpretation of elastic waves to electrical signals are the basis of AE testing. Analysis of these signals yield valuable information regarding the origin and importance of a discontinuity in a material. Specialized equipment is necessary to detect the wave energy and decipher which signals are meaningful.

2. Activity of AE Sources in Structural Loading:

AE signals generated under different loading patterns can provide valuable information **concerning the structural integrity** of a material. Load levels that have been previously exerted on a material do not produce AE activity. In other words, discontinuities created in a material do not expand or move until that former stress is exceeded.

This phenomenon, known as the **Kaiser Effect**, can be seen in the load versus AE plot to the right. As the object is loaded, acoustic emission events accumulate (segment AB). When the load is removed and reapplied (segment BCB), AE events do not occur again until the load at point B is exceeded.

As the load exerted on the material is increased again (BD), AE's are generated and stop when the load is removed. However, at point F, the applied load is high enough to cause significant emissions even though the previous maximum load (D) was not reached.



Basic AE history plot showing the **Kaiser Effect** (BCB).
The Felicity Effect (DEF) and emission during hold (GH).

This phenomenon is known as the **Felicity Effect**, can be quantified using the Felicity Ratio, which is the load where considerable AE resumes, divided by the maximum applied load (F/D).

Knowledge of the **Kaiser Effect and Felicity Effect** can be used to determine if major structural defects are present. This can be achieved by applying constant loads (relative to the design loads exerted on the material) and "listening" to see if emissions continue to occur while the load is held. As shown in the figure, if AE signals continue to be detected during the holding of these loads (GH), it is likely that substantial structural defects are present. In addition, a material may contain critical defects if an identical load is reapplied and AE signals continue to be detected.

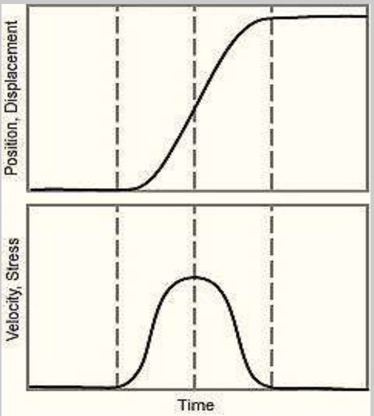
Noise in AE testing refers to **any undesirable signals** detected by the sensors. Examples of these signals include frictional sources (e.g. loose bolts or movable connectors that shift when exposed to wind loads) and impact sources (e.g. rain, flying objects or wind-driven dust) in bridges. Sources of **noise** may also be present in applications where the area being tested may be disturbed by **mechanical vibrations** (e.g. pumps).

To compensate for the effects of background noise, various procedures can be implemented. Some possible approaches involve fabricating **special sensors** with electronic gates for **noise blocking**, taking precautions to place sensors as far away as possible from noise sources, and electronic filtering (either using signal arrival times or differences in the spectral content of true AE signals and background noise).

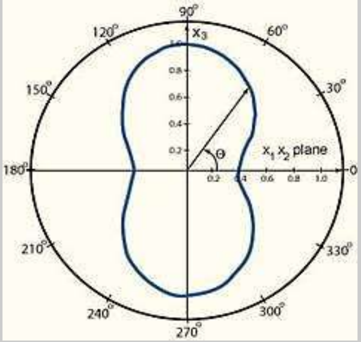
3. Theory of Acoustic Waves:

A primitive wave released at the AE source is illustrated in the figure right. The displacement waveform is a step-like function corresponding to the permanent change associated with the source process. The analogous velocity and stress waveforms are essentially pulse-like.

The width and height of the primitive pulse depend on the dynamics of the source process. Source processes, such as **microscopic crack jumps** and precipitate fractures are usually completed in a fraction of a microsecond or a few microseconds, which explains why the pulse is short in duration.



Primitive **AE wave** released at a source. The primitive wave is essentially a stress pulse corresponding to a permanent displacement of the material. The ordinate quantities refer to a point in the material.



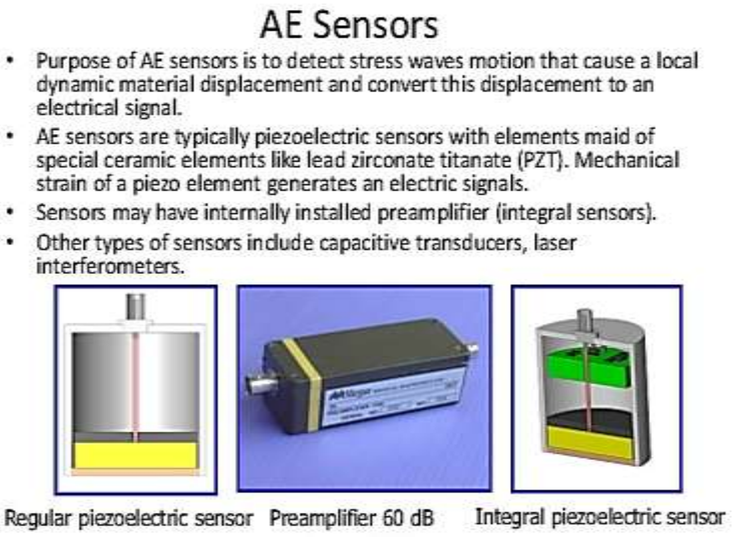
Angular dependence of acoustic emission radiated from a growing micro crack. Most of the energy is directed in the 90 and 270^{o} directions, perpendicular to the crack surfaces.

The amplitude and energy of the primitive pulse vary over an enormous range from submicroscopic dislocation movements to gross crack jumps. Waves **radiates from the source** in all directions, often having a strong directionality depending on the nature of the source process, as shown in the second figure. Rapid movement is necessary if a sizeable amount of the elastic energy liberated during deformation is to appear as an acoustic emission.

However, most materials-oriented researchers and **NDT inspectors** are not concerned with the **intricate knowledge of each source event**. Instead, they are primarily interested in the broader, statistical aspects of AE. Because of this, they prefer to use narrow band (resonant) sensors which detect only a small portion of the broadband of frequencies emitted by an AE.

These **sensors are capable of measuring hundreds of signals** each second, in contrast to the more expensive high-fidelity sensors used in source function analysis. The signal that is detected by a sensor is a combination of many parts of the waveform initially emitted. Acoustic emission source motion is completed in a few millionths of a second.

As the AE leaves the source, the waveform travels in a spherically spreading pattern and is reflected off the boundaries of the object. Signals that are in phase with each other as they reach the sensor produce constructive interference which usually results in the highest peak of the waveform being detected. The typical time interval from when an AE wave reflects around the test piece (repeatedly exciting the sensor) until it decays, ranges from the order of 100 microseconds in a highly damped, nonmetallic material to tens of milliseconds in a lightly damped metallic material.



AE Sensors

- Purpose of AE sensors is to detect stress waves motion that cause a local dynamic material displacement and convert this displacement to an electrical signal.
- AE sensors are typically piezoelectric sensors with elements maid of special ceramic elements like lead zirconate titanate (PZT). Mechanical strain of a piezo element generates an electric signals.
- Sensors may have internally installed preamplifier (integral sensors).
- Other types of sensors include capacitive transducers, laser interferometers.

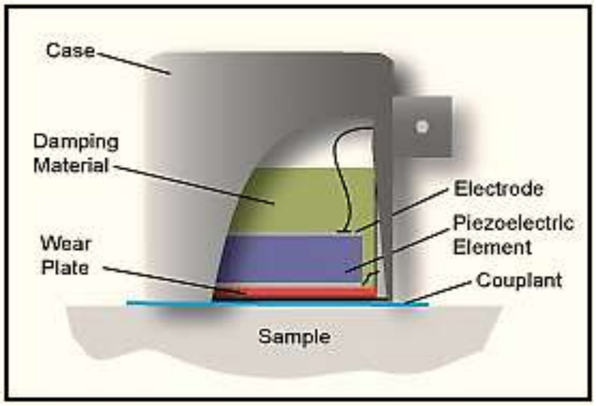
Regular piezoelectric sensor Preamplifier 60 dB Integral piezoelectric sensor

a. Attenuation: The intensity of an AE **signal detected by a sensor** is considerably lower than the intensity that would have been observed in the close proximity of the source. This is due to **attenuation**. There are **three main causes** of attenuation, beginning with geometric spreading. As an AE spreads from its source in a plate-like material, its amplitude decays by 30% every time it doubles its distance from the source. In three-dimensional structures, the signal decays on the order of 50%.

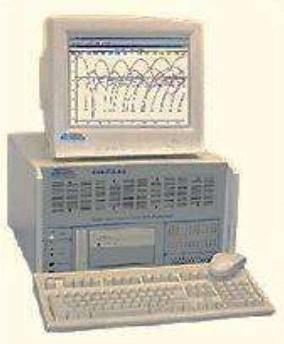
Measurements of the effects of attenuation on an AE signal can be performed with a simple apparatus known as a Hsu-Nielson Source. This consists of a **mechanical pencil** with either **0.3 or 0.5 mm** - **2H lead** that is passed through a cone-shaped Teflon shoe designed to place the lead in contact with the surface of a material at a 30 degree angle.

When the pencil lead is **pressed and broken** against the material, it creates a small, local deformation that is relieved in the form of a stress wave, similar to an AE signal produced by a crack. The simulated AE sources can be created at various sites on a structure to determine the optimal position for the placement of sensors and to ensure that all areas of interest are within the detection range of the sensor or sensors.

b. Acoustic Emission Equipment: The acoustic emission testing **can be performed in the field with portable instruments** or in a **stationary laboratory setting**. Typically, **systems contain a sensor, preamplifier, filter, and amplifier, along with measurement, display, and storage equipment** (e.g. oscilloscopes, voltmeters, and personal computers). Acoustic emission sensors respond to dynamic motion that is caused by an AE event. This is achieved through transducers which convert mechanical movement into an electrical voltage signal.

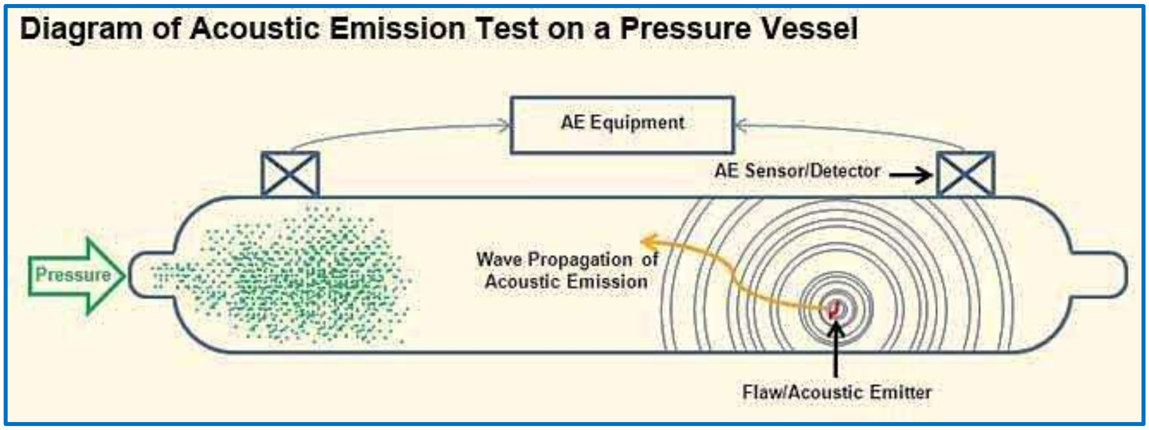


The **transducer element** in an AE sensor is almost always a **piezoelectric crystal**, which is commonly made from a **ceramic** such as **lead zirconate titanate** (PZT). Transducers are selected based on operating frequency, sensitivity and environmental characteristics, and are grouped into two classes: **resonant and broadband**. The majority of AE equipment is responsive to movement in its typical operating frequency range of **30 kHz to 1 MHz**. For materials with high attenuation (e.g. plastic composites), lower frequencies may be used to better distinguish AE signals.

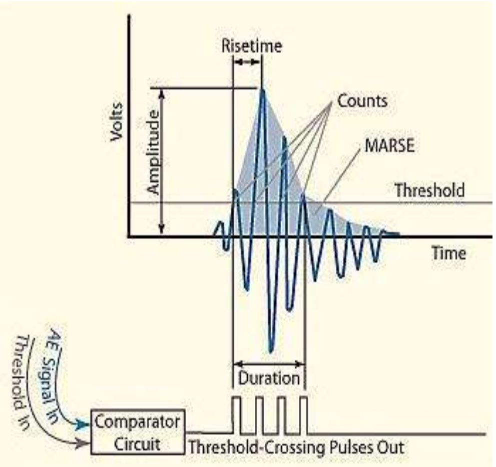


Thus, the AE signal that reaches the **computer mainframe** is free of a **background noise** and electromagnetic **interferences**. However, sensors and preamplifiers are designed to help eliminate unwanted signals. First, the preamplifier boosts the voltage to provide gain and cable drive capability.

To **minimize interference**, a preamplifier is placed close to the transducer; in fact, many transducers today are equipped with integrated preamplifiers. Next, the signal is relayed to a band pass filter for elimination of low frequencies (common to background noise) and high frequencies. The signal travels to the acoustic system mainframe and eventually to a computer or similar device for analysis and storage.



The **multiple-measurement circuits** can be used in multiple sensor/channel systems for source location purposes. At the measurement circuitry, the shape of the conditioned signal is compared with a threshold voltage value that has been programmed by the operator. Signals are continuous (analogous to Gaussian, random noise with amplitudes varying according to the magnitude of the AE events) or burst-type.



4. AE Signal Features:

With the equipment configured and setup complete, **AE testing may begin**. The sensor is coupled to the test surface and held in place with tape or adhesive. An **operator monitors** the signals which are excited by the induced stresses in the object. When a useful transient, or burst signal is correctly obtained, parameters like amplitude, counts, measured area under the rectified signal envelope (MARSE), duration, and rise time can be gathered. Each of the AE signal feature shown in the image is described below:

- **Amplitude, A**: Is the greatest measured voltage in a waveform and is measured in decibels (dB). This is an important parameter in acoustic emission inspection because it determines the detectability of the signal. Signals with amplitudes below the operator-defined, minimum threshold will not be recorded.

- **Rise time, R:** Is the time interval between the first threshold crossing and the signal peak. This parameter is related to the propagation of the wave between the source of the acoustic emission event and the sensor. Therefore, rise time is used for qualification of signals and as a criterion for noise filter.

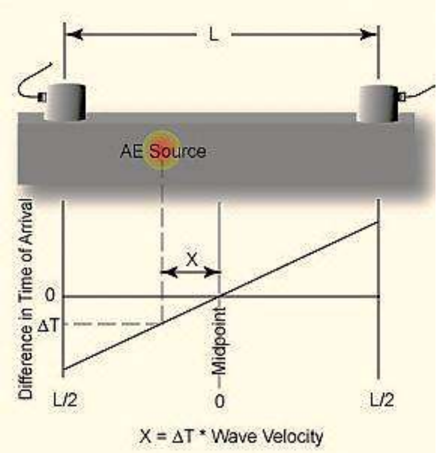
- **Duration, D**: Is the time difference between the first and last threshold crossings. Duration can be used to identify different types of sources and to filter out noise. Like counts (N), this parameter relies upon the magnitude of the signal and the acoustics of the material.

- **MARSE, E**: Sometimes referred to as energy counts, is the measure of the area under the envelope of the rectified linear voltage time signal from the transducer. This can be thought of as the relative signal amplitude and is useful because the energy of the emission can be determined. MARSE is also sensitive to the duration and amplitude of the signal, but does not use counts or user defined thresholds and operating frequencies. MARSE is regularly used in the measurements of acoustic emissions.

- **Counts, N**: Refers to the number of pulses emitted by the measurement circuitry if the signal amplitude is greater than the threshold. Depending on the magnitude of the AE event and the characteristics of the material, one hit may produce one or many counts. While this is a relatively simple parameter to collect, it usually needs to be combined with amplitude and/or duration measurements to provide quality information about the shape of a signal.

5. AE Source Location Techniques:

By properly plan spacing for the sensors, it is possible **to inspect an entire structure** with relatively few sensors. Source location techniques assume that AE waves travel at a constant velocity in a material. However, various effects may alter the expected velocity of the AE waves (e.g. reflections and multiple wave modes) and can affect the accuracy of this technique.

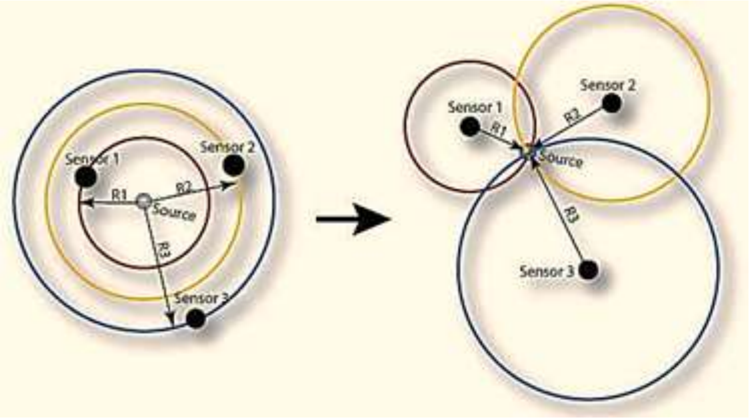


a. Multi-Channel Source Location Techniques:

Although the **magnitude of the damage** may be unknown after AE analysis, follow up testing at source locations can provide these answers. AE systems are capable of **using multiple** sensors/channels during testing, allowing them to record a hit from a single AE event.

The source can be located by knowing the velocity of the wave in the material and the difference in his arrival times among the sensors, as measured by hardware circuitry or computer software. Therefore, the geometric effects of the structure being tested and the **operating frequency of the AE** system must be considered when determining whether a particular source location technique is feasible for a given test structure.

b. Linear Location Technique: Several source location techniques have been developed based on this method. One of the commonly used computed-source location techniques is the linear location principle shown to the right. Linear location is often used to evaluate struts on truss bridges. When the source is **located at the midpoint**, the time of arrival difference for the wave at the two sensors is zero.

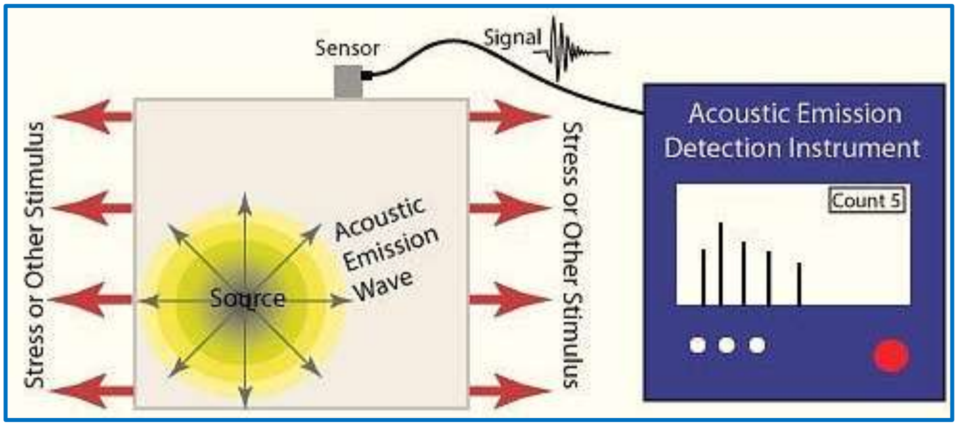


If the source is closer to one of the sensors, a difference in arrival times is measured. To calculate the distance of the source location from the midpoint, the arrival time is multiplied by the wave velocity. Whether the location **lies to the right or left** of the midpoint is determined by which sensor first records the hit. This is a linear relationship and applies to any event sources between the sensors.

c. Point Location: In order for point location to be justified, signals must be detected in a **minimum** number of sensors: **two for linear, three for planar, four for volumetric**. Accurate arrival times must also be available. Arrival times are often found by using peak amplitude or the first threshold crossing. The velocity of wave propagation and exact position of the sensors are necessary criteria as well.

6. Acoustic Emission Applications:

Acoustic Emission testing (AET) is been applied to inspect and monitor **pipelines, pressure vessels, storage tanks, bridges, aircraft, and bucket trucks**, and a variety of **composite and ceramic components**. It is also used in process control applications such as monitoring welding processes. A few examples of AET applications follow.



a. Welding Monitoring: During the welding process, **temperature changes** induce stresses between the **weld and the base metal**. These stresses are often **relieved by heat treating** the weld. However, in some cases tempering the weld is not possible and minor cracking occurs. Cracking can continue for up to **10 days after the weld** has been completed. ASTM E 749-96 is a standard practice of AE monitoring of continuous welding.

b. Bucket Truck Integrity Evaluation: Accidents, overloads and fatigue can occur with **bucket trucks** or any other aerial equipment. If a mechanical or structural defect is ignored, serious injury or fatality can result. Testing by independent labs and electrical utilities originally intended to examine only the boom sections, the method is now used for inspecting the pedestal, pins, and various other components.

Normally, the AE tests are second in a chain of inspections which start with visual checks. If necessary, follow-up tests take the form of magnetic particle, dye penetrant, or ultrasonic inspections. Experienced personnel can perform five to ten tests per day, saving valuable time and money along the way. ASTM F914 governs the procedures for examining insulated aerial personnel devices.

c. Gas Trailer Tubes: Acoustic emission testing on **pressurized jumbo tube trailers** uses hydrostatic retesting, where tubes must be removed from service and disassembled. A **10% over-pressurization** is performed at a normal filling station with AE sensors attached to the tubes at each end.

A multichannel acoustic system is used to detection and mapped source locations. Suspect locations are further evaluated using ultrasonic inspection, and when defects are confirmed the tube is removed from use. AET can **detect subcritical flaws** whereas **hydrostatic testing cannot detect** cracks until they cause rupture of the tube...

d. Bridges: Bridges contain many **welds, joints and connections**, and a combination of load and environmental factors heavily influence damage mechanisms such as fatigue cracking and metal thinning due to corrosion. Bridges receive a visual inspection every two years and when damage is detected, the bridge is either shut down; its weight capacity is lowered for more frequent monitoring.

Acoustic Emission is **increasingly being used** for bridge monitoring applications because it can continuously detect changes that may be due to damage without requiring lane closures or bridge shutdown. In fact, the proper **traffic flow** is commonly used to load or stress the bridge for the AE testing.

e. Aerospace Structures: Aerospace structures consist of complex assemblies of components that have been design to **carry significant loads** and this combination of requirements leads to many parts that can tolerate only a minor amount of damage before failing.

AET has found applications in monitoring the health of aerospace structures **because sensors can be attached** in easily accessed areas that are remotely located from damage prone sites. NASA's **Wing Leading Edge Impact Detection** System is partially based on

AE technology. The image at the right shows a technician applying AE transducers on the inside of the **Space Shuttle Discovery** wing structure. The impact detection system was developed to alert NASA officials to events such as the sprayed-on-foam insulation impact that damaged the Space Shuttle Columbia's wing leading edge during launch and lead to its breakup on reentry to the Earth's atmosphere.

f. AE Inspection on Other Materials: Such as, fiber-reinforced polymer-matrix composites, in particular glass-fiber reinforced parts or structures (e.g. fan blades) and material research (e.g. investigation of material properties, breakdown mechanisms, and damage behavior). Other inspections are:

- Inspection and quality assurance, (e.g. wood drying processes, scratch tests);
- Leakage test and location within various components (small valves, steam lines, tank bottoms);
- Detection and location of high-voltage partial discharges in transformers;
- Railroad tank car and rocket motor testing.

Note: There are a number of **standards and guidelines** that describe AE testing and application procedures as supplied by the American Society for Testing and Materials (ASTM). Examples are **ASTM E 1932** for the AE examination of small parts and **ASTM E1419-00** for the method of examining seamless, gas-filled, pressure vessels.

2. Infrared – Thermal Testing:

Thermal NDT methods involve the measurement or mapping of surface temperatures as heat flows to, from and/or through an object. The simplest thermal measurements involve making point measurements with a thermocouple. This type of measurement might be useful in locating hot spots, such as a roller bearing that is wearing out and starting to heat up due to an increase in friction.

(AKA Thermal Inspection, Thermography, Thermal Imaging, Thermal Wave Imaging and Infrared Testing)

The **image** above is a heat map of the space shuttle as it lands. In its more advanced form, the use of **thermal imaging** systems allow **thermal information** to be very rapidly collected over a wide area and in a non-contact mode. Thermal imaging systems are instruments that **create pictures of heat** flow rather than of light. Thermal imaging is a fast, cost effective way to perform detailed thermal analysis.

Thermal measurement methods have a **wide range of uses**. They are used by the police and military for night vision, surveillance, and navigation aid; by firemen and emergency rescue personnel for fire assessment, and for search and rescue; by the medical profession as a diagnostic tool; and by industry for energy audits, preventative maintenance, processes control and nondestructive testing.

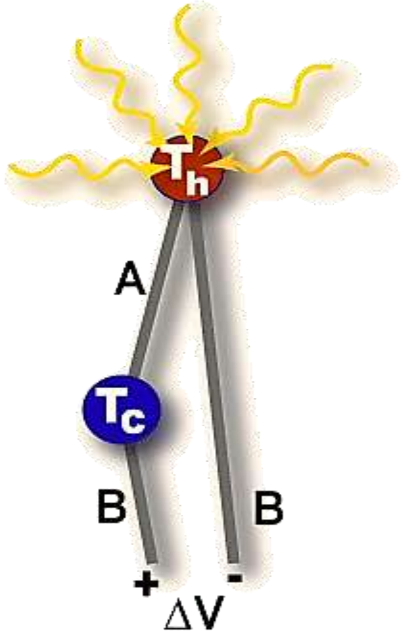
The basic premise of **thermographic NDT** is that the flow of heat from the surface of a solid is affected by internal flaws such as disbonds, voids or inclusions. The use of thermal imaging systems for industrial NDT applications will be the focus of this material.

1. Infrared Energy Development:

Sir William Herschel, an astronomer, **is credited** with the discovery of **infrared energy in 1800**. Knowing that sunlight was made up of all the colors of the spectrum, Herschel wanted to explore the colors and their relationship to heat. He devised an experiment using a prism to spread the light into the color spectrum and thermometers with blackened bulbs to measure the temperatures of the different colors.

Herschel observed an **increase in temperature from violet to red** and observed that the hottest temperature was actually beyond red light. Herschel termed the radiation causing the heating beyond the visible red range "calorific rays." Today, it is called "**infrared**" energy.

2. The Thermocouples:



In 1821, **Thomas Johann Seebeck** found that a circuit made from **two dissimilar metals**, with junctions at different temperatures, would deflect a compass needle. He initially believed this was due to magnetism induced by a temperature difference, but soon realized that it was an electrical current that was induced.

More specifically, the **temperature difference** produces an electric potential (voltage) which can drive electric current in a closed circuit. Today, this is known as the **Seebeck effect**. The Seebeck voltage does not depend on the distribution of temperature along the metals between the junctions. This is the **physical basis for a thermocouple**, which was invented by **Nobili, in 1829**.

3. Noncontact Thermal Detectors:

Melloni soon used the **thermocouple technology** to produce a device called the **thermopile that** is an instrument made of **thermocouple junction pairs** connected electrically in series. The absorption of thermal radiation by one of the thermocouple junctions, called the active junction, increases its temperature.

The **thermoelectric effect** is the **differential temperature** between the active junction and a reference junction kept at a fixed temperature that produces an **electromotive force** directly proportional to the differential temperature created. Melloni was able to show that a person **30 feet away** could be **detected** by focusing his or her thermal energy on the thermopile.

Thermopile detectors **are used today** for spectrometers, process temperature monitoring, fire and flame detection, presence monitor, and a number of other non-contact temperature measurement devices. A device similar to the thermopile measures a change in electrical resistance, was named **bolometer**. In 1880 it was shown that it could **detect a cow over 1000 feet away**.

The first experiment with **photo conducting detectors** was used during **World War I** with **thallium sulfide detectors** that produced signals of infrared photons and were faster and much more sensitive than other thermal detectors. During **World War II**, **photoconductive or quantum detectors** were further refined and this resulted in a number of **military applications**, such as target locating, tracking, weapons guiding and intelligence gathering.

4. Imaging Systems:

IR imaging technology was **developed for the military use** and then to **commercial markets** in the **1960s**. Initial applications were in laboratory level R&D, preventative maintenance applications, and surveillance. The first portable systems suitable for **NDT applications** were produced in the **1970s**. These systems utilized a **cooled scanned detector** and the image **quality was poor** by today's standards.

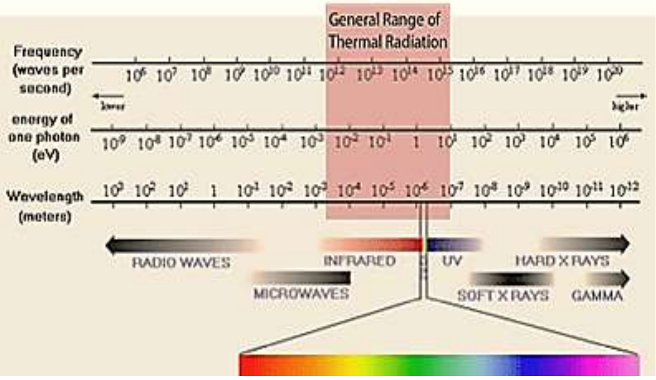
In the late **1980s**, the US military released the **Focal Plane Array (FPA) technology** into the commercial marketplace. The FPA uses a large array of tiny IR sensitive semiconductor detectors, similar to those used in **Charge Couple Device (CCD) cameras**. This resulted in a dramatic **increase in image quality**. The advances in computer technology and **image processing programs** helped to simplify data collection and to improve data interpretation.

Note: In **1992**, the **American Society for Nondestructive Testing** officially **adopted infrared testing** as a standard test method. Today, a wide variety of thermal measurement equipment is commercially available and the technology is heavily used by industry. Researchers continue to improve systems and explore new applications.

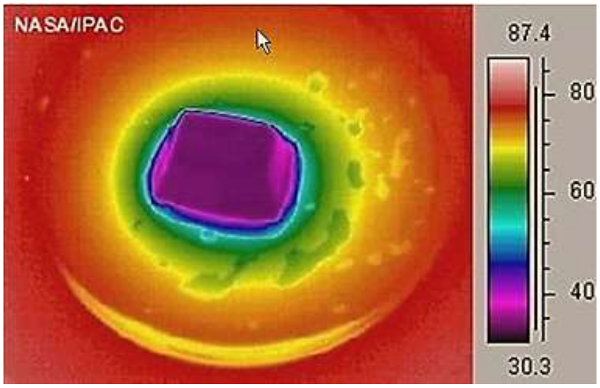
5. Thermal Energy Theory:

Energy comes in **many forms**, and it can **change from one form to another but can never be lost**. This is the **First Law of Thermodynamics**. A byproduct of nearly all energy conversion is **heat**, also known as **thermal energy**. When there is a temperature difference between two objects or two areas within the same object, **heat transfer occurs**.

Heat energy transfers from the **warmer areas to the cooler areas** until **thermal equilibrium** is reached. This is the **Second Law of Thermodynamics**.



When the temperature of an object is the same as the surrounding environment, it is said to be at ambient temperature. The **wavelength** of thermal radiation extends from **0.1 microns to several hundred mi-**



crons, as highlighted in the image. This means that not all of the heat radiated from an object will be visible to the human eye, but the heat is detectable.

Consider the gradual heating of a piece of steel. With the application of a heat source, heat radiating from the part is felt long before a change in color is noticed. If the heat intensity is great enough and applied for long enough, the part will gradually change to a red color. The heat that is felt prior to the part changing color is the radiation that lies in the infrared frequency spectrum of electromagnetic radiation.

Above there is an infrared image of an **ice cube melting**. Note the temperature scale on side, which shows warm areas in red and cool areas in purple. It can be seen that the ice cube is colder than the surrounding air and it is absorbing heat at its surface. The basis for infrared imaging technology is that any object whose temperature is above **0°K radiates** infrared energy.

Infrared (IR) radiation has a wavelength that is longer than visible light or, in other words, greater than **700 nanometers**. As the wavelength of the radiation shortens, it reaches the point where it is short enough to enter the visible spectrum and can be detected with the human eye. An infrared camera has the ability to detect and display infrared energy.

Even **very cold objects radiat**e some infrared energy. Even though the object might be absorbing thermal energy to warm itself, it will still emit some infrared energy that is detectable by sensors. The amount of radiated energy is a function of the object's temperature and its relative efficiency of thermal radiation, known as emissivity.

6. Heat Transfer Mechanisms:

Thermal **energy transfer** occurs through three mechanisms: **conduction, convection, and/or radiation**. **Conduction** occurs **primarily in solids** and to a **lesser degree** in **fluids** as warmer, more energetic molecules transfer their energy to cooler adjacent molecules. **Convection** occurs in **liquids and gases**, and involves the mass movement of molecules such as when stirring or mixing is involved.

The **third way that heat** is transferred is through **electromagnetic radiation** of energy. Radiation needs no medium to flow through and, therefore, can **occur even in a vacuum**. Electromagnetic radiation is produced when **electrons lose energy** and fall to a lower energy state. Both the wavelength and intensity of the radiation is directly related to the temperature of the surface molecules or atoms.

a. Emissivity: Radiation heat transfer is the emissivity of the object being evaluated. Emissivity is a measure of a surface's efficiency in transferring infrared energy. It is the ratio of thermal energy emitted by a surface to the energy emitted by a perfect blackbody at the same temperature. A perfect **blackbody only exists in theory** and is an object that absorbs and reemits all of its energy.

Human skin is nearly a perfect blackbody as it has an **emissivity of 0.98**, regardless of actual skin color. If an object has low emissivity, IR instruments will indicate a lower temperature than the true surface temperature. For this reason, most systems and instruments provide the ability for the operator to adjust the emissivity of the object being measured. Sometimes, **spray paints, powders, tape or "emissivity dots"** are used to improve the emissivity of an object.

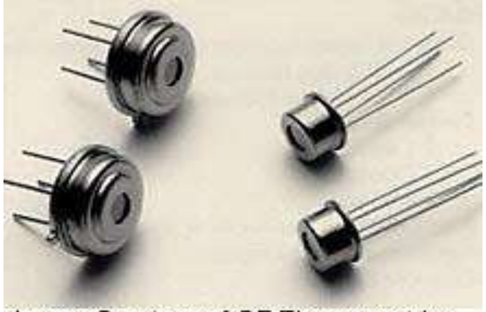


Image Courtesy of GE Thermometrics

b. Thermal Detectors: **Thermal detectors** include heat sensitive coatings, thermoelectric devices and pyroelectric devices. Heat **sensitive coatings** range from simple wax-based substances that are blended to melt at certain temperatures to specially formulated paint and greases that change color as temperature changes.

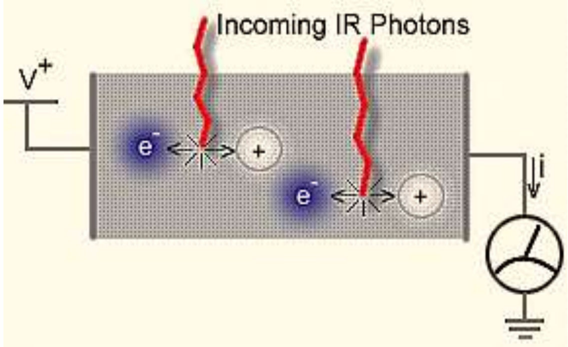
Thermal energy detection and measurement equipment comes in a large variety of forms and levels of sophistication. One way to categorize the equipment and materials is to separate thermal detectors from quantum (photon) detectors. The basic distinction between the two is that thermal detectors depend on a two-step process.

The absorption of thermal energy in these detectors raises the temperature of the device, which in turn changes some temperature-dependent parameter, such as electrical conductivity. Quantum devices detect photons from infrared radiation. **Quantum detectors** are much more sensitive but require **cooling** to operate properly.

Heat sensitive coatings are relatively inexpensive but do not provide good quantitative data. **Thermoelectric devices** include **thermocouples, thermopiles** (shown right), **thermistors and bolometers**. These devices produce an **electrical response** based on a change in temperature of the sensor. They are often used for point or localized measurement in a contact or near contact mode. However, thermal sensors can be miniaturized.

For example, **micro bolometers** are the **active elements** in some high-tech portable imaging systems, such as those used by fire departments. Benefits of thermal detectors are that the element **does not need to be cooled** and are comparatively low in price. Thermal detectors are used to **measure the temperature** since **home appliances**, fire and intruder detection systems, industrial furnaces to rockets.

c. Quantum (Photon) Detectors: Unlike thermal detectors, **quantum detectors** do not rely on the conversion of incoming radiation to heat, but **convert** incoming photons directly into an electrical signal. When **photons** in a particular range of wavelengths are absorbed by the detector, they create free electron-hole pairs, which can be detected as electrical current.



The **signal output** is very small and is overshadowed by noise generated internally. Since this noise within a semiconductor is partly proportional to temperature, quantum detectors are operated at **cryogenic temperatures**, down to **77 °K** (liquid nitrogen) or **4 °K** (liquid helium)] to minimize noise. However, their **superior electronic performance** still makes them the detector of choice for the bulk of thermal imaging applications. Some systems can detect temperature differences as small as **0.07°C**.

d. Cooling the Detector: There are several different ways of **cooling the detector** to the required temperature. In the early days of thermal imaging, **liquid nitrogen** was poured into imagers to cool the detector. Although satisfactory, the logistical and safety implications led to the development of other cooling methods. High pressure gas can be used to cool a detector to the required temperatures.

The gas is allowed to rapidly expand in the cooling systems and this expansion results in the significant reduction in the temperature of a gas. Mechanical cooling systems are the standard for portable imaging systems. These have the logistical advantage of freeing the detection system from the requirements of carrying high pressure gases or liquid nitrogen.

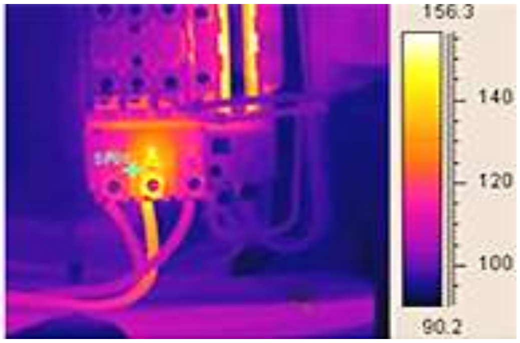
7. Equipment - Imaging Technology:

Thermal imaging instruments **measure radiated** infrared energy and also converts the data to corresponding maps of temperatures. A true thermal image is a gray scale image with hot items shown in white and cold items in black. Some thermal imagers have the ability to add color, which is artificially generated by the camera's video enhancement electronics, based upon the thermal attributes seen by the camera.

Some instruments provide temperature data at each image pixel. **Cursors** can be positioned on each point, and the **corresponding temperature is read out** on the screen or display. Images may be digitized, stored, manipulated, processed and printed out. Industry-standard image formats, such as the file **format (TIFF)**, which permit files to work with a wide array of commercially available software packages.

Images are produced either by **scanning a detector** (or group of detectors) or by using with focal plane array. A scanning system in its simplest form could involve a single element detector scanning along each line in the frame (serial scanning). In practice, this would require very high scan speeds, so a series of elements are commonly scanned as a block, along each line. The use of multiple elements eases the scan speed requirement, but the scan speed and channel bandwidth requirements are still high.

Another way thermal images are produced is known as staring arrays. The spatial resolution of the image is determined by the number of pixels of the detector array. Common formats are **320 by 240 pixels** (320 columns, 240 rows), and **640 by 480**. The latter format is nearly the resolution of a standard TV. The ability to measure temperatures on small areas, can be as fine as **15 microns**. Temperature resolution, the ability to measure small temperature differences, can be as fine as **0.1° C**.

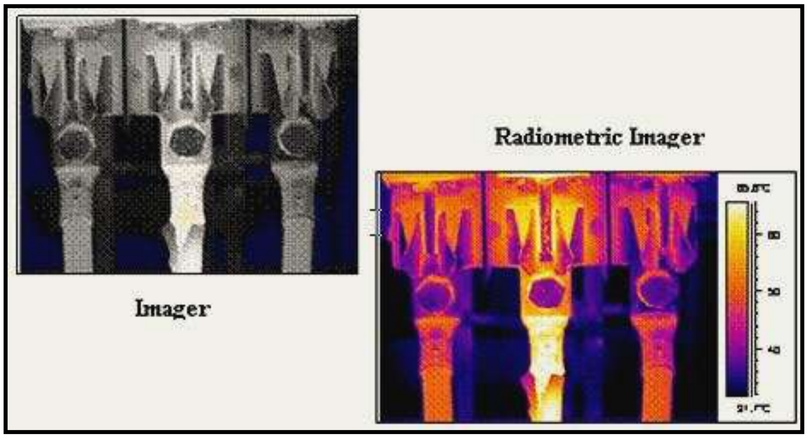


a. Equipment for Establishing Heat Flow: In some inspection applications, such as **corrosion or flaw detection**, the components being inspected may be at ambient temperature and heat flow must be created. Heating can be accomplished by placing the part in a warm environment, such as a **furnace**, or directing heat on the surface with a heat gun or with flash lamps. Alternately, **cooling** can be accomplished by placing the component in a cold environment or cooling the surface with a spray of cold liquid or gas.

b. Image Capturing and Analysis: **IR cameras** are commonly used with an external heat source can often detect large, near-**surface flaws**. However, repeatable, quantifiable detection of deeper, subtler features requires the additional sensitivity of a sophisticated computerized system. In these systems, a computer is used to capture a number of time sequence images which can be stepped through or viewed as a movie to evaluate the thermal changes in an object as a function of time.

This technique is often referred to as thermal wave imaging. The image to the right **shows a pulsed thermography system**. This system uses a closely controlled burst of thermal energy from a **xenon flash lamp** to heat the surface. The dissipation of heat is then tracked using a high speed thermal imaging camera. The equipment was designed to inspect the **fuselage skins of aircraft for corrosion damage** and can make quantitative measurements of material loss.

c. Image Interpretation: Most thermal imagers **produce a video output** in which white indicates areas of maximum radiated energy and black indicates areas of lower radiation. The **gray scale image** contains the maximum amount of information. However, in order to ease general interpretation and facilitate subsequent presentation, the thermal image can be **artificially colorized**, by allocating desired colors to blocks of grey levels to produce the familiar colorized images. This enables easier **image interpretation** and may be enhanced to show particular energy levels in detail.



8. Electromechanical Infrared Inspection:

Electrical and mechanical systems can have an unexpected shutdown and could have a major impact on production. Then, thermal inspection is a valuable and **cost-effective diagnostic** tool with many industrial applications. With an **infrared camera**, the inspector can see the **change in temperature** from the surrounding area, identify whether or not it is abnormal and predict the possible failure.

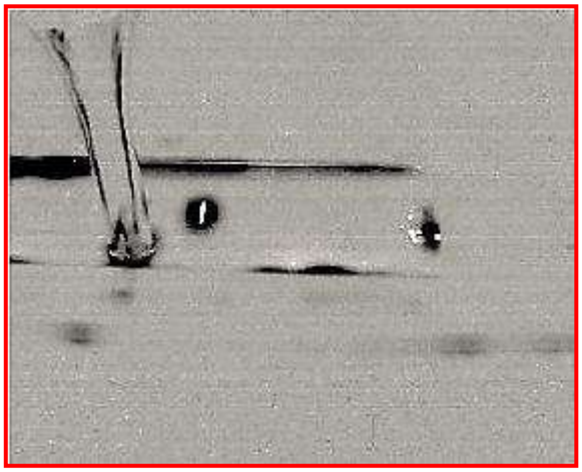
Infrared testing can locate loose electrical connections, failing transformers, improper bushing and bearing lubrication, overloaded motors or pumps, coupling misalignment, and other applications where a change in temperature will indicate an undesirable condition. Since typical **electrical failures** occur when there is a temperature rise of **over 50°C**, problems can be detected well in advance of a failure. The **image on the right** above shows three electrical connections. The middle connection is hotter than the others.

a. Vibrothermograph or Thermosonic Testing: Is a new technique that was recently introduced by researchers at Wayne State University for the **detection of cracks**. A solid sample is excited with bursts of high-energy, low-frequency acoustic energy. This causes frictional heating at the faces of any cracks present and hotspots are detected by an **infrared camera**.

Despite the apparent simplicity of the scheme, there are a number of experimental considerations that **can complicate** the implementation of this technique. Factors including acoustic horn location, horn-crack proximity, horn-sample coupling, and effective detection range all significantly affect the degree of excitation that occurs at a crack site for a given energy input.

b. Infrared Techniques: Can also be used to **detect flaws** in materials or structures. The inspection techniques can monitor the flow of heat from the surface of a solid and how this flow is affected by **internal flaws,** such as disbonds, voids or inclusions. Sound material, a good weld, or a solid bond will see the heat dissipate rapidly through the material, whereas a defect will retain the heat for longer.

Below are **two images** from an **IR camera** showing a **0.050" thick** 7075 aluminum plate sample with a **prefabricated crack** being inspected using a commercial **Vibrothermograph** system. The image **on the left** is the IR image with a pre-excitation image subtracted.

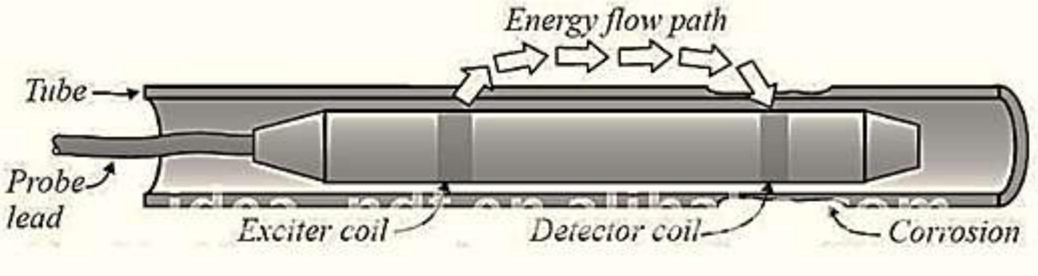


A **crack** can be seen in the **middle** of the sample and just to the right of the ultrasonic horn. Also seen is heating due to the friction at various clamping sites, and reflection from the hole at the right edge of the sample. The image **on the right** is the same data with image processing performed to make the **crack indication** easier to distinguish.

3. Remote Field Testing (RFT):

The Remote Field Testing or "RFT" is one of several **electromagnetic testing methods** commonly employed in the field for remote nondestructive testing. Other electromagnetic inspection methods include the **Magnetic Flux Leakage**, conventional **Eddy Current and Alternating Current Field Testing**. The Remote Field Testing (RFT) is **associated** with Eddy Current Testing (ET) and the term "Remote Field Eddy Current Testing" is often used to describe remote field measurements. There are several major differences between Eddy Current Testing and Remote Field Testing as described below.

The RFT is primarily used to **inspect ferromagnetic tubing** and conventional Eddy Current techniques have **difficulty** inspecting the **full thickness** of the tube wall, due to the strong skin effect in ferromagnetic materials. For example, using **conventional Eddy Current** probes to inspect a steel pipe **10 mm** thick (such as what might be found in heat exchangers) would require frequencies around **30 Hz** to achieve the adequate I.D. to O.D. penetration through the tube wall. The use of **such a low frequency** results in a very **low sensitivity** of flaw detection.

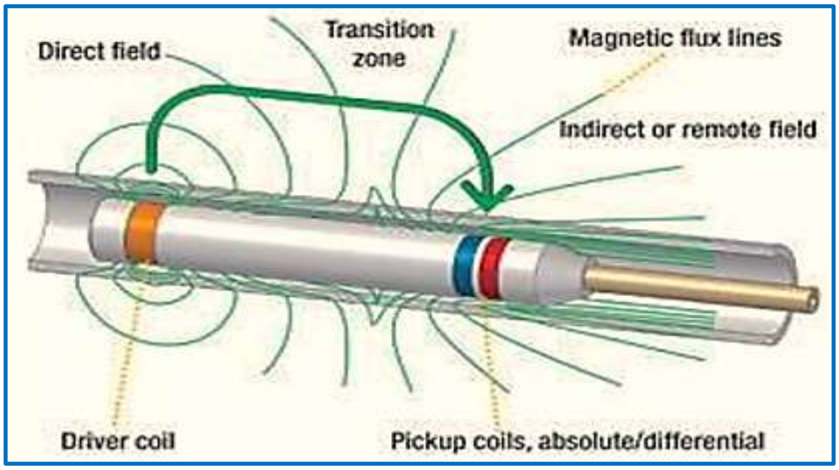


Typical RFT probe. In comparison with conventional Eddy Current, RFT coils are widely spaced in order to measure the though-transmission field

The **RFT method** has the advantage of allowing nearly **equal sensitivities of detection** at both the inner and outer surfaces of a ferromagnetic tube. The method is highly sensitive to variations in wall thickness and tends to be less sensitive to fill-factor changes between the coil and tube. The RFT can be used to **inspect any conducting tubular** product, but it is generally **considered to be less sensitive** than conventional Eddy Current techniques, when **inspecting non-ferromagnetic materials**.

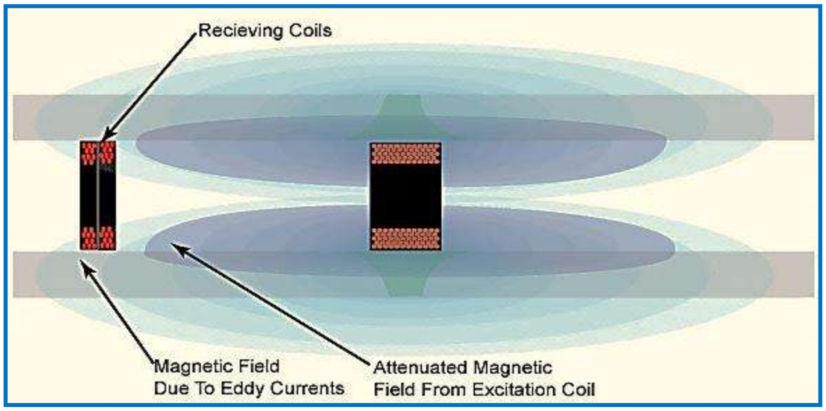
1. RFT Theory:

A probe consisting of an **exciter coil** and one or more detectors is pulled through the tube. The exciter coil and the detector coil(s) are rigidly fixed at an axial distance of two tube diameters or more between them. The exciter coil is driven with a **relatively low frequency sinusoidal current** to produce a magnetic field. This changing magnetic field induces strong circumferential eddy currents which extend axially, as well as radially in the tube wall.

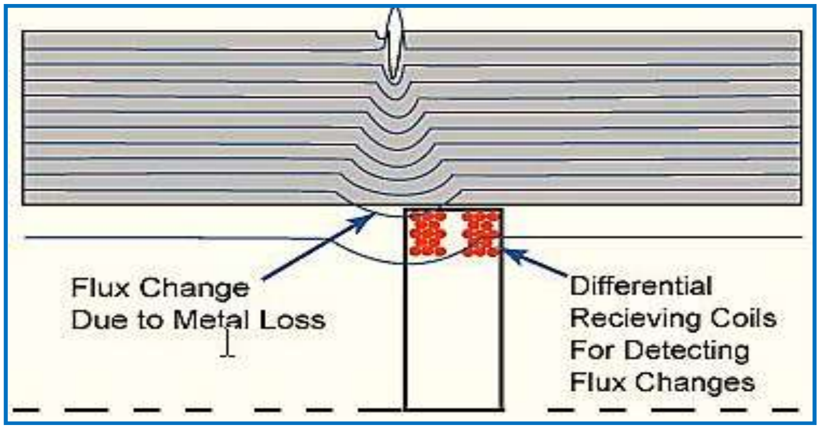


These Eddy currents, produce their **own magnetic field**, and oppose the magnetic field from the exciter coil. The magnetic field from the eddy currents extends farther along the tube axis. The **interaction be-**

tween the two fields is that the exciter field is dominant near the exciter coil and the eddy current field becomes dominant at some distance away from the exciter coil.



The receiving coils are positioned at a distance where the magnetic field from the eddy currents is dominant, placed at a **distance where they are unaffected by the magnetic field** from the exciter coil but can adequately measure the field strength from the secondary magnetic field. The electromagnetic induction occurs as the changing magnetic field cuts across the coil array. The strength of the magnetic field at this distance from the excitation coil is weak, but sensitive to changes in the pipe wall from the I.D. to the O.D.



2. RFT Probes:

Probes mainly for pipe inspection of pipe and tubing are typically of the bobbin (ID) variety. These probes use either a **single or dual excitation coil** to develop an electromagnetic field through the pipe or tube. The excitation coils are driven by alternating current. The sensing coil or coils are located a few tube diameters away in the remote field zone.

These probes can be used in differential or absolute modes for detection of general **discontinuities, pitting, and variations** from the I.D. in ferromagnetic tubing. To insure maximum sensitivity, each probe is specifically designed for the inside diameter, composition, and the wall thickness of a particular tube.

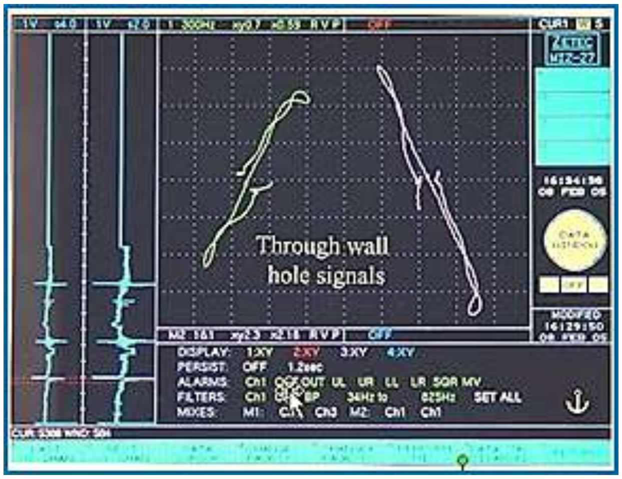
3. RFT Instrumentation:

a. Eddy Current: Instruments generally used for RFT inspection are often the **dual type Eddy Current** instruments that employ **multi-frequency technology**. The receiving coil voltage is typically in the micro-volt range, so an amplifier is required **to boost** the signal strength. Certain systems incorporate a probe excitation, known as **multiplexing**, that utilizes an extreme high speed switching method to excite the probe, at more **than one frequency** in sequence.

b. Simultaneous Injection: Is another method of coil excitation that may be used with RFT. The exciter coil is excited with **multiple frequencies** at the same time while incorporating filter schemes that subtract aspects of the acquired data. The **instrument monitors** the pickup coils and **passes the data** to the display section of the instrument. Some systems are **capable of recording** the data to some type of storage device for later review.

4. RFT Signal Interpretation:

The signals obtained are **very similar** to those obtained with **conventional Eddy Current Testing**. When all the proper conditions are met, changes in the phase of the receiver signal with respect to the phase of the exciter voltage are directly proportional to the sum of the wall thickness within the inspection area. Localized changes in **wall thickness** result in phase and amplitude changes. These changes can be indicative of defects such as cracks, corrosion pitting or corrosion/erosion thinning.



```
DISPLAY:   1:XY   2:XY   3:XY   4:XY
PERSIST:   OFF    1.2sec
ALARMS:    Ch1  OFF OUT  UL  UR  LL  LR  SQR MV
FILTERS:   Ch1  OFF BP   34Hz to   825Hz   SET ALL
MIXES:     M1:  Ch1  Ch3  M2:  Ch1  Ch1
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```
DISPLAY:   1:XY   2:XY   3:XY   4:XY
PERSIST:   OFF    1.2sec
ALARMS:    Ch1  OFF OUT  UL  UR  LL  LR  SQR MV
FILTERS:   Ch1  OFF BP   34Hz to   825Hz   SET ALL
MIXES:     M1:  Ch1  Ch3  M2:  Ch1  Ch1
```

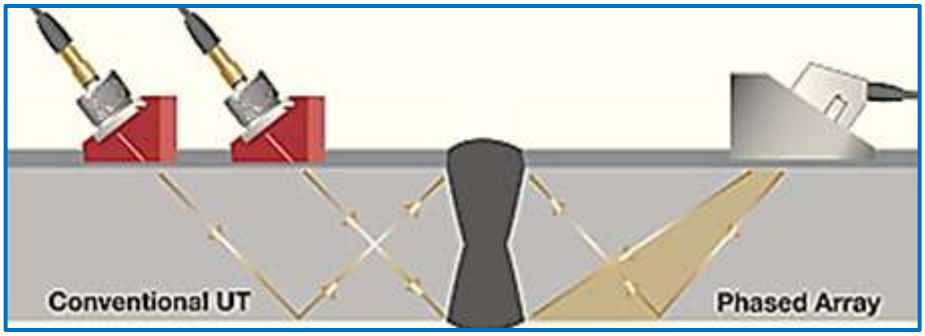
5. RFT Reference Standards:

The reference standards for the **RFT inspection of tubular products** used for manufacturing calibration must closely match the physical and chemical properties of the inspection specimen. Some of the important properties that must be considered include **conductivity, permeability and alloy content**. In addition, tube dimensions including I.D., O.D. and wall thickness must also be controlled.

4. Phased Array Ultrasonics (PA):

Phased Array Ultrasonics (PA) is an advanced method of **ultrasonic testing beam** array that has applications in **medical imaging,** as noninvasively examine the **heart** or to **find flaws** in manufactured materials, such as welds. Single-elements (non-phased array) probes, known technically as **monolithic** probes, emit a **beam** in a fixed direction. To test a large volume of material, a conventional probe must physically scan (move or turn), to **sweep the beam** through the area of interest.

The beam is controllable because a **phased array probe** is made up of **multiple small elements**, each of which can be pulsed individually at a computer-calculated timing. The term ***phased*** refers to the ***timing***, and the term ***array*** refers to the ***multiple elements***. Phased Array Ultrasonic testing is based on principles of **wave physics**, which also have applications in fields such as optics and electromagnetic antennae.



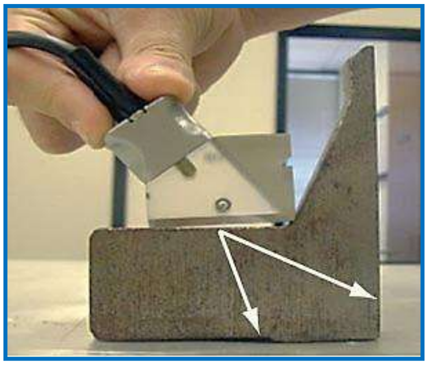
Note: Phased array transmission was **originally developed in 1905** by Nobel Laureate **Karl Ferdinand Braun,** who demonstrated enhanced **transmission of radio waves** in one direction. During World War II, Nobel Laureate **Luis Alvarez** used phased array transmission in a **rapidly-steerable radar** system for "ground-controlled approach", a system to **aid in the landing** of aircraft.

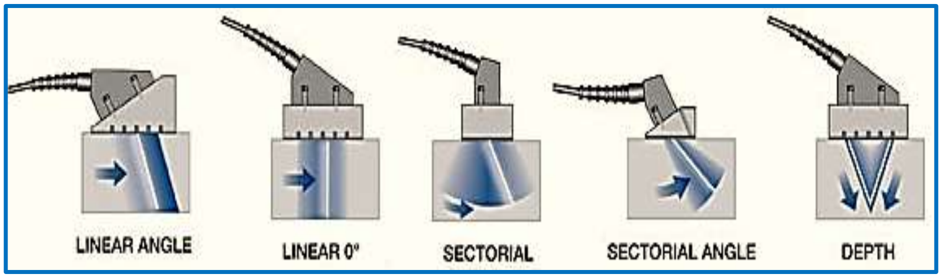
1. Principle of Operation:

Ultrasonic waves are mechanical vibrations using **piezo crystal** probes elements consisting of linear array with 16 crystal elements, excited by an electrical voltage. Typical frequencies of ultrasonic waves are in the range of **0.1 MHz to 50 MHz**. Phased Array commonly require frequencies between **0.5 MHz and 15 MHz** (million cycles per second). In conventional UT, the frequency value must be kept between **0.1 to 1 MHz.**

Conventional ultrasonic inspections use **mono-crystal** probes with divergent sound waves. The ultrasonic field propagates along an **acoustic** axis with a single refracted angle. The divergence of this beam is the only "additional" angle, which might contribute to detection and sizing of small cracks.

The **Phased Array Ultrasonics probe** consists of **many small ultrasonic transducers**, each of which can be pulsed independently. By varying the timing, for instance by pulsing the elements one by one in sequence along a row, a pattern of constructive interference is set up, which results in a beam at a set angle. In other words, the **beam** can be steered electronically. The **beam is swept** like a **search-light** through the tissue or object being examined, and the data from multiple beams are put together to make a visual image showing a slice through the object.





In the figure above the **element** emits a pressure wave that spreads out like a **ripple** on a pond (largest semicircle). The **second to right element** is pulsed next, and emits a **ripple** that is slightly smaller than the first because it started later. The **process continues down** the line until **all the elements** have been pulsed. The multiple waves travel at a set angle. In other words, the beam angle can be set just by programming the pulse timings.

Thus, the main essence of Phased Array testing is that an ultrasonic beam, whose direction (refracted angle) and focus can be steered electronically, by varying the excitation delay of individual elements or groups of elements. This beam steering permits multiple angles and/or multiple point inspections from a single probe and a single probe position.

2. Phased Array Application:

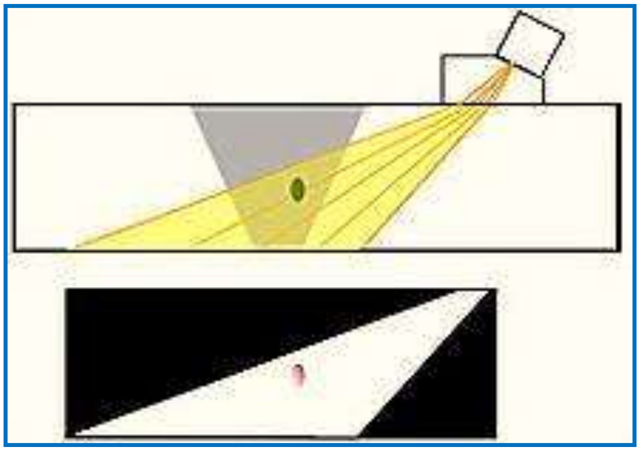
Phased array is **widely used in several industrial sectors**, such as construction or power generation. This method is an advanced NDT method that is used to detect component failures, **i.e., cracks or flaws** and to determine the **component quality**. Due to the possibility to control parameters such as beam angle and focal distance, this method is **very efficient** regarding the defect detection and speed of testing.

Phased array technology is an **ultrasonic method** with the capability of setting beam parameters, such as angle, focal distance, and focal point size through software. Phased arrays allow the replacement of multiple inspections and mechanical components. Inspecting parts with variable-angle beams maximizes detection regardless of the defect orientation, while optimizing signal-to-noise ratio.

a. Advantages of Phased Array for Pipe Welds:

- Auditable, repeatable results (i.e. full data storage);
- High quality inspections, especially for planar defects;
- Fast and accurate;
- Much simpler and safer (i.e. radiation issues);
- No disruption of production;
- Adaptable to many different configurations and applications.

b. Field Construction Pipelines: At a construction site, a technician tests a pipeline weld for defects using an Ultrasonic Phased Array instrument. The scanner, consists of a frame with magnetic wheels, holds the probe in contact with the pipe by a spring. The wet area is the ultrasonic couplant that allows the sound to pass into the pipe wall.



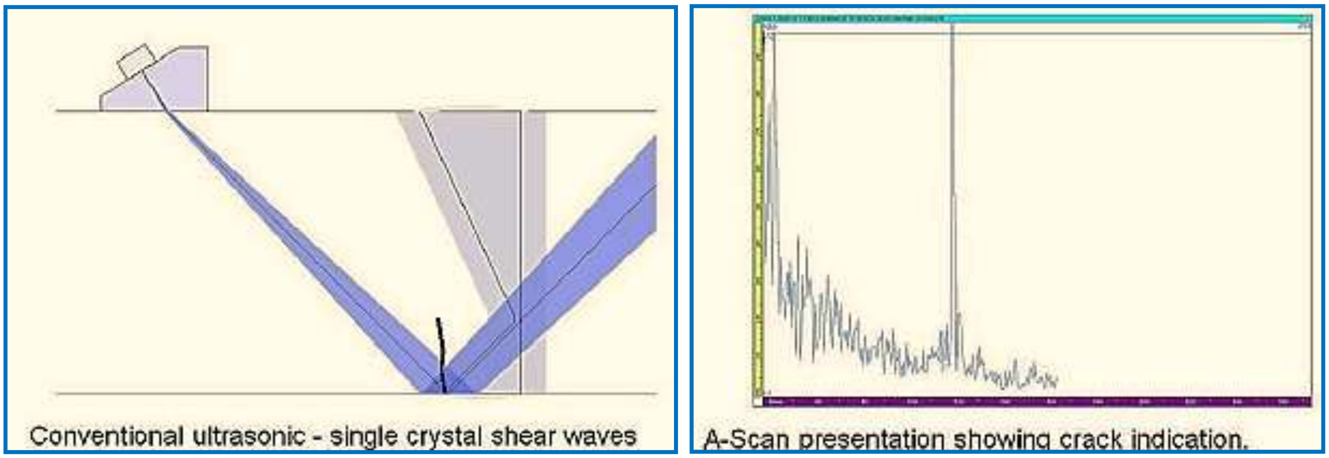
When welding is examined by Phased Array, the probe emits a **series of beams to flood the weld** with sound. The flaw appears as a **red indication** on the instrument screen, as indicated at left image. Apart from **detecting flaws** in components, **Phased Array Ultrasonics** (PA) can also be used for **wall thickness** measurements in conjunction with **corrosion testing** and for the following industrial purposes:

- Inspection of Welds;
- Thickness measurements;
- Corrosion inspection;
- Flaw detection;

c. Naval Usage: Phased array radar systems **are also used by** warships of many navies**.** Due the rapidity with which the beam can be steered, phased array radars allow a warship to use **one radar system** for surface detection and **tracking** (finding ships)**,** air detection and tracking (finding aircraft and missiles) and missile uplink capabilities. Each surface-to-air **missile** in flight is required a dedicated fire-control radar**,** which means that ships could only engage a small number of simultaneous targets.

Ultrasonic **crack detection and sizing** is an essential tool in determining the asset integrity of pressure vessels and piping. The **conventional Ultrasonic Testings** (UT) is **tedious** and time consuming. In the field, cracks were **manually plotted** on full scale cross-sectional sketches to characterize, located position, verify ID connection, orientation and depth.

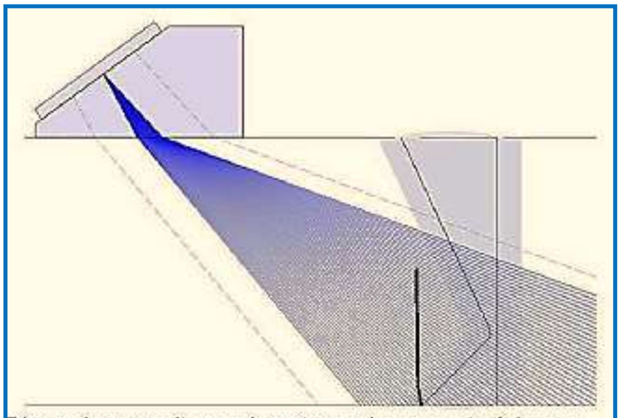
Furthermore, **back-scattering tip signals** were absent with conventional UT. Crack interaction with weld anomalies presents further complications to verify **separation and crack interaction**. If separation could not be confirmed, conservative values result in erroneous data for crack growth rates and repairs. The **images, below**, illustrate the **crack positions**, providing the ability to distinguish a series of welding discontinuities from cracks.


Conventional ultrasonic - single crystal shear waves

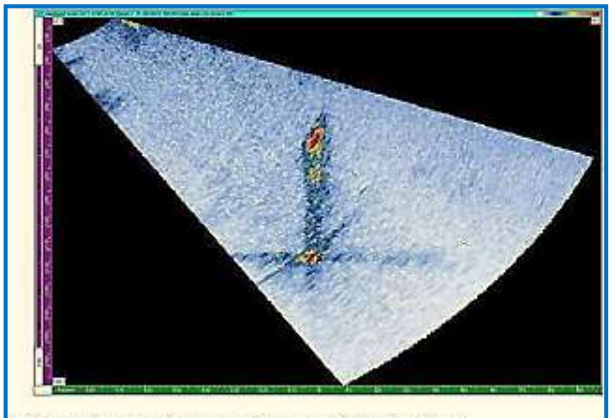
A-Scan presentation showing crack indication.

Sketch showing conventional ultrasonic technology with A-Scan presentation.

d. Inspection Time: The Phased Array Ultrasonics **testing below** shows the crack propagation angle, ID connections, depth and orientation. This has subsequently **reduced the inspection time** to approx. 50% to that previously found with **conventional UT**, including supplemental sizing for nozzles from Ø12" to Ø30" in wall thickness of 52 mm to 100 mm.

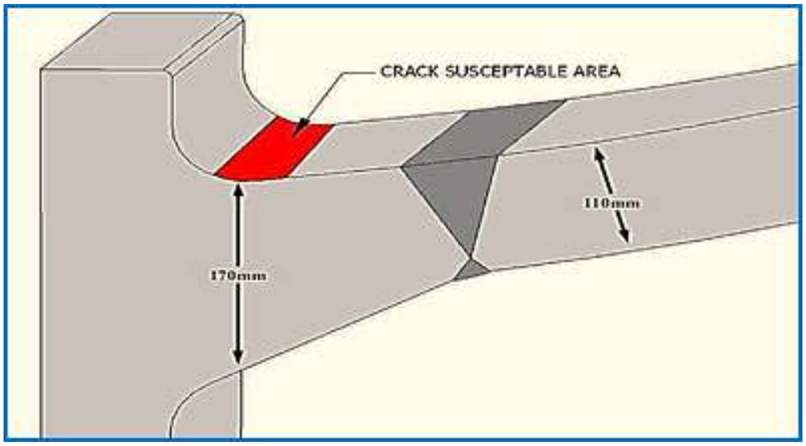


Phased array ultrasonic setup using a sectorial scan

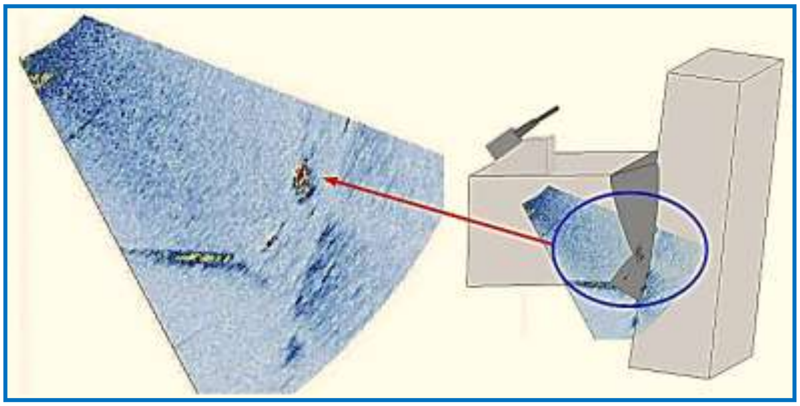


Phased array image of a crack indication.

e. Focal Beam Steering: Below is shown a piece with a crack susceptible area in red, identified by Finite Element Analysis (FEA). Conventional UT **was difficult** with long sound paths, using 60º shear waves due to beam spread. Phased array **provided a solution** with variable focal depths and beam steering. Strong **backscatter tip-diffraction** signals become apparent, for variable offsets as some nozzles interacted with head knuckle curvatures.



Below, is shown another example of **weld discontinuities** encountered during inspections. This was an example of incomplete cross-penetration. Fatigue crack noted on fillet weld toe, shell side. Weld discontinuities in weld on fusion face. Weld area is exaggerated by previous weld repairs.



f. Potential Advantages: Ultrasonic Phased Arrays present major improvements over conventional ultrasonics for inspecting pipeline girth welds, both for **onshore and offshore**. Probe pans are lighter and smaller, permitting less cutback; scans are quicker due to the smaller probe pan; phased arrays are considerably more flexible for changes in pipe dimensions or weld profiles and for different scan patterns. More important, some of the potential advantages of phased arrays are now becoming commercially available. These applications include the following:

- ✓ Compensating for variations in seamless pipe wall thickness;
- ✓ Premium inspections for risers, tendons, and other components;
- ✓ Small-diameter pipes;
- ✓ Clad pipe;
- ✓ Special weld profiles;
- ✓ Double jointing;
- ✓ Seam weld inspections;
- ✓ Portable phased arrays for tie-ins and repairs;
- ✓ Software modifications.

From a practical viewpoint, Ultrasonic Phased Arrays are merely a **method of generating and receiving** ultrasound. However, many of the details of ultrasonic inspection remain unchanged. For example, **if 7.5 MHz** is the **optimum inspection frequency** with conventional ultrasonics, then Phased Arrays would typically **use the same frequency**, **focal length**, and **incident angle**. Anyway, a prepared setup is quick, in comparison with **adjusting** conventional transducers. The information is recorded in a file and only takes seconds to reload.

Phased arrays permit **to combine** electronic scanning, sectorial scanning, and precision focusing to give a practical combination of displays. Optimum angles can be selected for welds and other components, while electronic scanning permits fast and functional inspections. For zone discrimination scans of pipeline welds, specific angles are used for given weld geometries, as shown above. These features are defined by **ASTM E-1961-98**. The other codes are API 1104, DNV OS101, and ISO 13847.

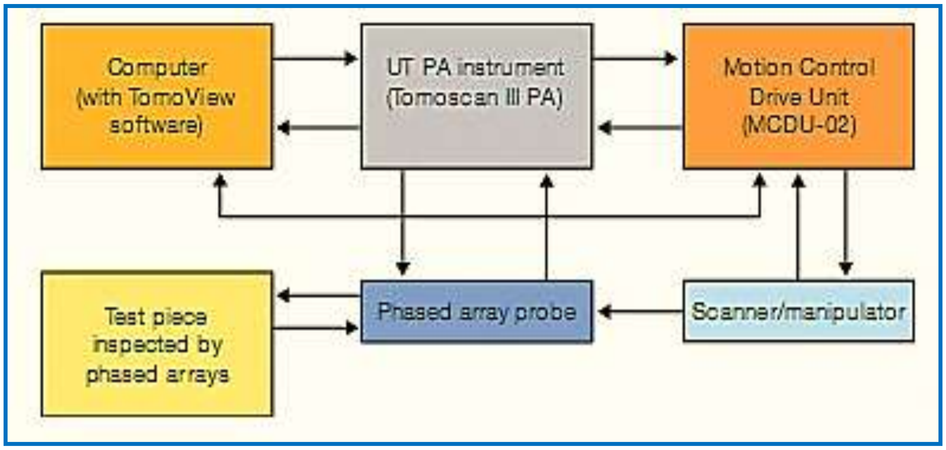
3. Basic Components of a PA Array System:

Phased Array Ultrasonics (PA) shows **significant reductions in scanning times**, proving to be a valuable asset for complex geometries, indicating the direction of propagation via imaging. The resulting data is accurate and reliable. Conventional UT is frequently questionable and tip diffraction signals are not apparent, limiting sizing techniques. The **main components** for a basic scanning system with Phased Array instruments are presented below:

The use of composite phased array transducers with multiple angles scans, the tip signals are easy to identify. The Phased Array Ultrasonics (PA) technology can provide novel solutions to these problems with **reliable results**, imaging of the cracks showing direction or propagation and reduced inspection times. Phased array inspection times are typically quicker, at least 50% time reduction over conventional UT techniques, resulting in less down time for vessels passing cost savings to the owner, as described:

- ✓ New techniques in detection and sizing where previous conventional UT was not feasible;
- ✓ Data is stored for trending, reporting, auditing, per review and comparison purposes;

- ✓ Focal laws can be changed during inspection for each situation, thus optimizing tip signals and accuracy of depth measurements;
- ✓ Data can be projected onto 2D and 3D sketches for interpretation, thereby allowing easier communication and reporting of results to the customer;
- ✓ Imaging shows the crack face, tip and direction of propagation; all valuable information.



5. Time of Flight Diffraction (TOFD):

Time-of-Flight Diffraction (TOFD) is another method of ultrasonic testing, more sensitive and accurate for the nondestructive **testing of welds**. TOFD was invented in the UK in the 1970s initially as a research tool. The use of TOFD **enabled crack sizes** to be measured more accurately, so that expensive components could be kept in operation as long as possible with minimal risk of failure.

In a TOFD system, a pair of ultrasonic probes sits on **opposite sides of a weld**. One of the probes, the transmitter, emits an ultrasonic pulse that is picked up by the probe on the other side, the receiver. In undamaged pipes, the signals picked up by the receiver probe are from two waves: one that travels along the surface and one that reflects off the far wall.

When a **crack** is present, there is a **diffraction of the ultrasonic wave** from the tip(s) of the crack. Using the measured pulse of the Time-of-Flight, the **depth of a crack tip** can be **calculated** automatically by simple trigonometry. This method is even **more reliable** than traditional Radiography, manual Pulse Echo and Automated Weld testing methods.

1. TOFD Units:

The Time-of-Flight amplitude analysis technique, utilizes **multiple search units** in automatic **pulse-echo**, transmitter-receiver, or tandem configuration. The selectable parameters control the compression, using a pattern-recognition algorithm, so that only the relevant scan amplitudes are stored and further processed.

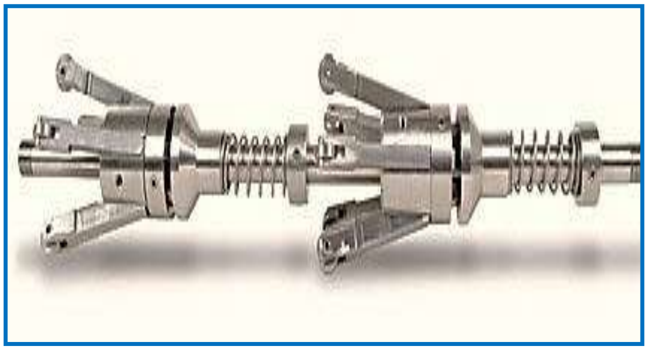
These raw data can be displayed in B-, C-, and D-scan (side, top, and end view) presentations, with selectable color-code increments for amplitude and fast zoom capabilities. A **two-dimensional spatial-filtering algorithm** is applied to search for correlation of the time-of-flight raw data with reflector-typical time-of flight trajectories.

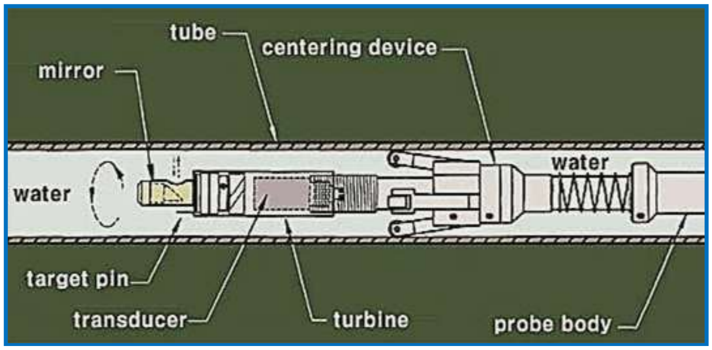
2. Features:

- ✓ Fast computerized and automatic systems for long length weld inspection.
- ✓ Probes are mounted on a moving device that travels along a weld, recording data as it moves.
- ✓ TOFD is sensitive to cracks and measures their dimensions accurately.
- ✓ TOFD has two blind zones, not sensitive to defects, supplemented by a conventional pulse-echo examination of the near and far walls, commonly mounted as the TOFD probes.
- ✓ Requires ultrasound technicians with advanced training.

6. Internal Rotary Inspection System (IRIS):

IRIS is another ultrasonic method for the nondestructive testing of **pipes and tubes,** since the quality of pipes diminishes after some time. The IRIS **probe is inserted into a tube that is flooded with water**, and the probe is pulled out slowly as the **data is displayed and recorded**. The ultrasonic beam allows **detection of metal loss** from the **inside and outside** of the tube wall.





The IRIS probe **consists of a rotating mirror** that directs the ultrasonic beam **into the tube wall**. The mirror is **driven by a small turbine** that is rotated by the pressure of water being pumped in. As the probe is pulled inside the pipe; the spinning motion of the mirror **results in a helical scan** path. The Internal Rotary Inspection System (IRIS) is a technique that is extremely suitable for **inspecting both ferritic and nonferritic pipes**, to measure wall thicknesses very accurately. However, the method is **far slower** than eddy current inspection for example.

Internal and external defects can be **detected not only the depth** but also the geometry. Because the method is based on reflecting ultrasonic pulses, it is important that the pipes are **very clean inside**. Soiling in the pipe can adversely influence the accuracy of measurement. The transducer utilized for the inspection has to be fast (frequency) enough to bounce back at both inner wall and outer wall.

1. IRIS Application:

IRIS is field-proven and commonly used in **boilers, heat exchangers, and fin-fan tubes**. Often used as a back-up to electromagnetic examination of tubes, to verify calibration and accuracy. It is especially useful, as a follow-up to remote field testing, due to the full sensitivity near the tube support structures.

2. IRIS Examination:

The IRIS probe must be **moved very slowly**, approximately 1 inch per second (2.5 cm/s). The wall thickness measurements are typically accurate to within 0.005 inch (0.13 mm). For the very smallest and thinnest tubes it is usually used a 25 MHz. piezoelectric transducer. Before the examination, tubes must **be cleaned** on the inside to **bare metal**. A supply of **clean water** is needed, typically at a pressure of **60 psi** (0.4 MPa). Dirt or debris in the water may cause the turbine to jam. It works for tube diameters of ½ inch (13 mm) and up. Special centralizing devices are needed for larger diameters.

- Works in metal or plastic tubes;
- Typical smallest detectable defect, hole of diameter 1/16-inch (1.6 mm;
- Operates in temperatures above freezing;
- Can pass bends, but will not detect defects in bends;
- Not sensitive to cracks aligned with tube radius;
- It reveals both uniform corrosion and localized pitting corrosion;
- Can inspect tube wall thickness from 0.8 mm;

Results:

- ✓ Provide data of full length of a tube;
- ✓ Provide report in exact remaining wall thickness;
- ✓ Identify the type of flaw indication such as localized wall loss, gradual corrosion and pitting;
- ✓ Indication of OD flaw or ID flaw.

7. Other Specialized NDT Techniques:

Beyond IRIS, pipelines can be examined with penetrating electromagnetic radiation, such as **X-rays or 3D X-rays** for volumetric inspection. Sound waves utilize the Ultrasonic testing. Simple contrast between a defect and the bulk of a sample may be enhanced by **Visual examination**. The Liquid Penetrant testing involves using dyes, fluorescent or non-fluorescing, in fluids for non-magnetic materials, usually metals.

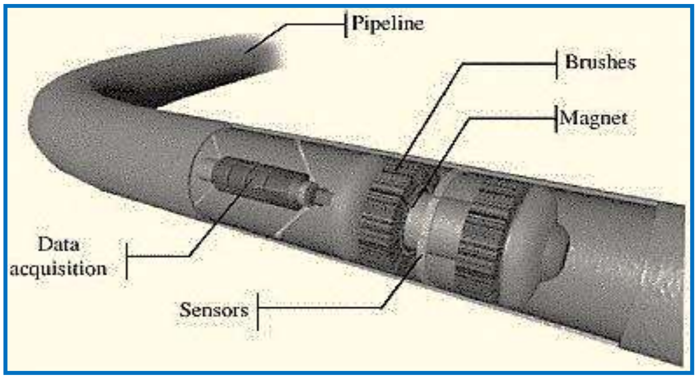
Magnetic Particle testing involves using a **liquid suspension** of fine iron particles applied to a part, while it is externally applied magnetic field. The Thermoelectric Effect (or Seebeck effect) uses **thermal properties** of an alloy to quickly and easily characterize many alloys.

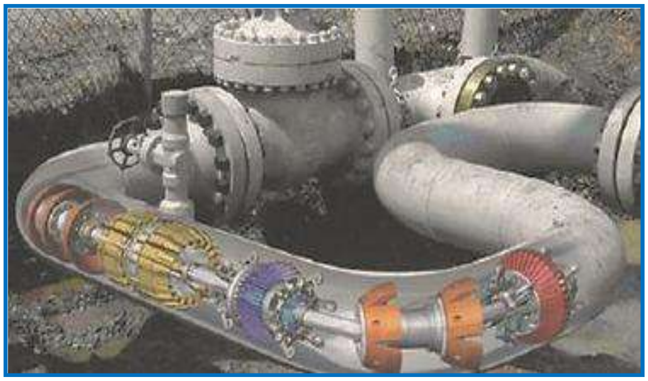
The Chemical Spot Test method, utilizes application of sensitive chemicals to indicate the metal quality and presence of **alloying elements**. Electrochemical methods use electrochemical **fatigue crack sensors**, to inspect the tendency of **metal oxidizing**, before progressive damage.

The various methods, due to their particular natures, may **require very special techniques** to certain applications. Therefore choosing the right method is an important part of the performance of NDT. Other **common** specialized techniques are:

1. Magnetic Flux Leakage (MFL):

The Magnetic Flux Leakage technique (MFL) is used for detecting materials “crack-like” or “type flaws” and "far-side flaws", to evaluate quantitatively the **metal loss area due to pitting or local corrosion** in oil-storage tank floors or underground steel pipes. A powerful magnet is used to **magnetize the steel**, with a magnetic detector placed between the poles, to detect the leakage field.



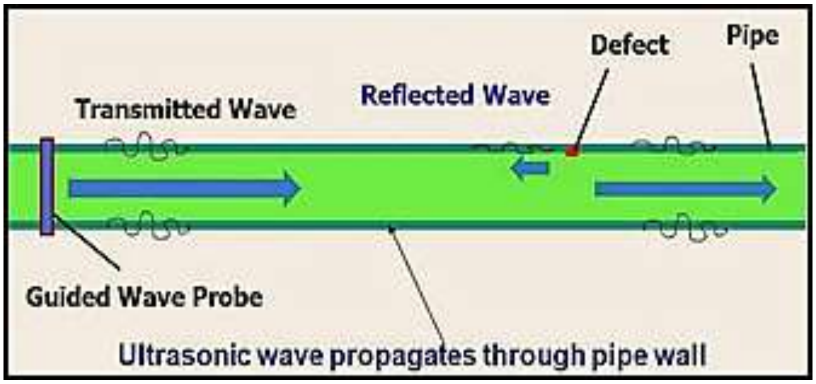


Then, analysts interpret the chart recording of the leakage field to identify damaged areas and to estimate the depth of metal loss. In the field, **a device that travels inside a pipeline** to clean or inspect it is typically known as a **"PIG"**. The PIGs are built to **match the diameter** of a pipeline and use the very product being carried to end users to transport them.

Pigs have been used in pipelines and have many uses. Some are used to separate one product from another, some clean and other inspect. This type of MFL tool is known as an **"intelligent" or "smart" inspection PIG** because its electronics collects data in real-time while travelling through the pipeline. PIG electronics, allow tool detect features as small as 1 cm square.

2. Guided Wave Testing (GWT):

The Guided Wave Testing (GWT) method employs **mechanical stress waves** that propagate **along a structure length** while guided by its boundaries. This allows the waves to **travel long distances** with little loss in energy. Nowadays, GWT is widely used to inspect and screen many engineering structures, particularly for the inspection of **metallic pipelines** around the world.



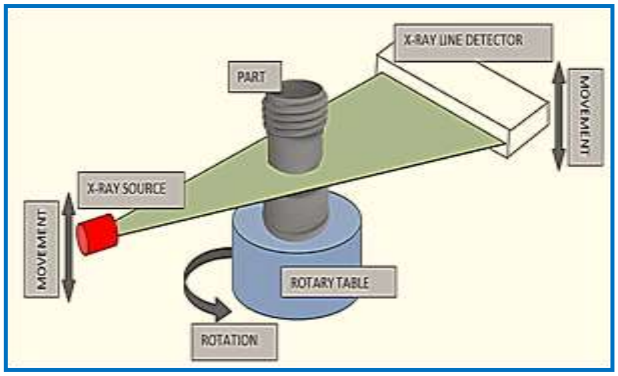
Unlike conventional Ultrasonics, there are an infinite number of guided wave modes, grouped into three families, the **torsional, longitudinal and flexural modes**, since the acoustic properties are a function of the **pipe geometry**, the material and the frequency. The properties of these wave modes often relies on heavy mathematical modeling, typically presented in graphical plots called Dispersion curves.

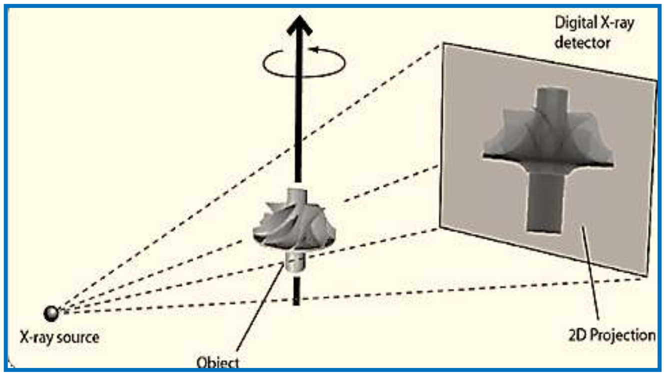
In Guided Wave Testing of pipelines, an **array of low frequency transducers** is attached around the circumference of the pipe to generate an axially symmetric wave that propagate along the pipe in both the forward and backward directions of the transducer array.

3. Industrial Computed Tomography (CT):

It is a process which uses **X-ray equipment** to produce 3D or 2D representations of components both externally and internally. The **CT scanning** have been also used for flaw detection, failure analysis, metrology, assembly analysis and reverse engineering applications. One of the most recognized forms of analysis using CT is assembly or visual analysis, **to see inside** a component in their functioning position or be analyzed without disassembly.

Today, machine or equipment parts can be manufactured around the world, **designed** in one country, **machined** in another and **assembled** in a third. CT allows the comparison of parts using the CAD data. The deviations of external and internal geometries appear on the surface colour map through **3D representation or in 2D windows**. This process is beneficial when comparing the parts from various suppliers, studying the differences from one cavity to another of the same casting mold, or verifying the complete design.





8. Materials - Quality Identification:

1. Chemical Spot Test:

Spot test or point analysis is a generic term referring to sensitive and selective tests based on **chemical reactions**, wherein use of a drop of the reagent solution is an essential step. The tests are micro analytical in nature and are applicable to the **investigation of metallic materials**. An important part of spot test analysis is played by the actual manipulation of unknown substances and reagents, and the method is not dependent on the use of auxiliary optical magnification.

In general, spot tests are the **ultimate in simplicity**, since the method derives from the nature of the reagents used, together with the advantageous use of reaction conditions. The utmost sensitivity and selectivity can be obtained with a minimum of physical and chemical operations.

Essential requirements for the successful application of spot test procedures include a **knowledge of the chemical basis** of all details of the tests used, strict observance of trustworthy experimental conditions, scrupulous cleanliness of the laboratory and equipment, and use of only the purest reagents available. Tests should be repeated to assure reproducibility. Both blanks and controls always should be run.

2. Positive Material Identification (PMI):

Positive Material Identification (PMI) gives alloy chemistry identification instantly using a handheld analyzer without having to transport, alter, or damage the material. Many industries, including the petroleum refining and petrochemical, use the **Thermo Scientific X-ray Fluorescence (XRF) analyzer** for positive identification of simple carbon, alloys and stainless steel materials.

The emphasis on safety and accident prevention has increased in public scrutiny, stepped-up industrial safety regulations, and more stringent OSHA oversight and fines. This means that **Positive Material Identification (PMI)** in alloys used throughout the physical plant is **no longer a choice, but a necessity**. Today's best practices include 100% positive material testing of all critical materials.

The steel materials that can be easily identified on site field are; rods, bars, tubing, piping, wire strands and so on; finished welds and weld beads; bolts, rivets and fasteners; valves and flanges; complete reaction vessels, etc. Industry organizations have also worked to develop guidelines to assure that the nominal compositions of all **alloy components** in a process system are consistent with design specifications. The advantages are:

- Rapidly verify alloys in seconds;
- Recover lost material traceability;
- Isolate finished welds to validate filler material composition and dilution rates;
- Confirm the integrity of process piping, valves, and reaction vessels;
- XRF instruments offer fast, accurate alloy identification and elemental analysis.

3. Stainless Steel Identification:

The tests defined below are intended for rapid, inexpensive and non-destructive on-site sorting of grades of stainless steel, when, for example, bars of grades 304 and 303 have been accidentally stored together, or grade 304 and 316 plates are mixed.

- **Magnetic Response:** Austenitic (Type 300) stainless steels. These steels are called **magnetic**, due they are attracted to a magnet, including the **ferritic, duplex, martensitic** and precipitation hardening stainless steels. Other **non-magnetic** steels are the **austenitic manganese** steels.

- **Nitric Acid Reaction:** Stainless steels from non-stainless steels. The testing piece of the steel is put under strong nitric acid (20% to 50%) at room temperature, or a drop of the acid on a cleaned surface of the steel.

- **Molybdenum Spot Test (Mo):** The most common stainless steels are types 404 to 316, but the following grades also contain sufficient Mo to give a positive response to this test: 316, 316L, 317, 317L, 444, 904L, 2205, 4565S and all "super duplex" grades (S32760 / Zeron 100 / S32750, etc.

- **Sulphur Spot Test (S):** Stainless and plain carbon steels containing at least 0.1% Sulphur, or free machining grades. (S1214, S12L14, 303, 416, 430F).

These tests are extremely useful, but it is important to realize that they have limitations. For instance, it is not possible to readily sort 304 from 321, 316 from 316L or 304 from 304L. The **Molybdenum Spot Test** therefore indicates that a piece of steel **contains Mo**, but does not alone indicate 316. In the absence of other knowledge the steel could be 316L, 2205 or 904L, etc.

In most cases, if these simple tests are not sufficient to **identify the product** it is best to have a full **spectrometric analysis** carried out by a competent laboratory. Product **colour codes, tags and stickers** and stamped or stenciled Heat/Grade/Specification markings should be retained as much as possible.

4. ASME/ASTM E1476 - Standard Guide for Metals Identification:

ASME/ASTM E1476 describes the general requirements, methods, and procedures for the nondestructive identification and sorting of metals. It provides guidelines for the **selection and use of methods** to establish and maintain the identity of metals **from melting to their final application**. This involves the use of **standard quality assurance** practices and procedures throughout various stages of manufacturing and processing, at warehouses and materials receiving, and during fabrication and final installation.

Nondestructive methods have the potential for monitoring grade during production on a continuous or statistical basis, for monitoring properties such as **hardness and case depth**, and for verifying the effectiveness of heat treatment, cold-working, and so on.

Spectrometric analysis instruments respond to the presence of alloying constituents. The **electromagnetic (eddy current) and thermoelectric methods**, on the other hand, are among those that respond to properties in the sample that are affected by chemistry and processing, with indirect information on composition and mechanical properties.

The term "**nondestructive**" includes techniques that **may require the removal** of small amounts of metal during the examination, without affecting the serviceability of the product. The nondestructive methods covered in this guide provide quantitative and qualitative information on metals properties, as follows:

a. Quantitative:

- ✓ X-ray fluorescence spectrometry;
- ✓ Optical emission spectrometry.

b. Qualitative:

- ✓ Electromagnetic (eddy current);
- ✓ Conductivity/resistivity;
- ✓ Thermoelectric;
- ✓ Chemical spot tests;
- ✓ Turboelectric;
- ✓ Spark testing (special case).

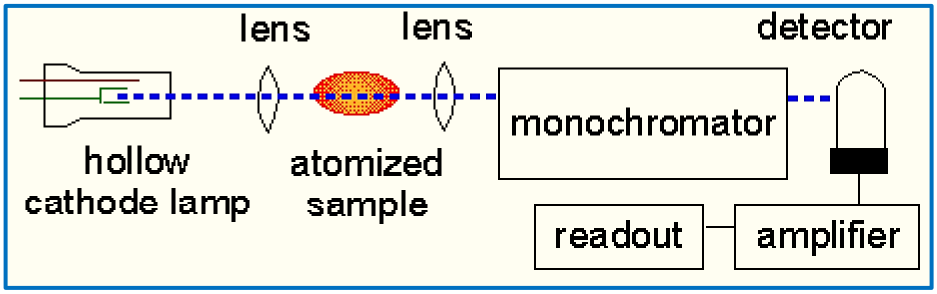
5. Spectrometry:

The spectrometer is an apparatus used to split light into an array of separate colors, called as spectrum, which utilizes the phenomenon of optical dispersion. The light from a source can consist of a continuous spectrum, an emission spectrum (bright lines), or an absorption spectrum (dark lines). Because each element leaves its spectral signature in the pattern of lines observed, a spectral analysis can reveal the composition of the object being analyzed. Generally, a spectrum is a graph that shows intensity as a function of wavelength, of frequency, of energy, of momentum, or of mass.

The most used spectrometers are; the optical spectrometers that show the intensity of light, which has a function of wavelength or of frequency and the mass spectrometer, which consists of three components: an ion source, a mass analyzer, and a detector. The ionizer converts a portion of the sample into ions. The deflection is produced either by refraction in a prism or by diffraction in a diffraction grating.

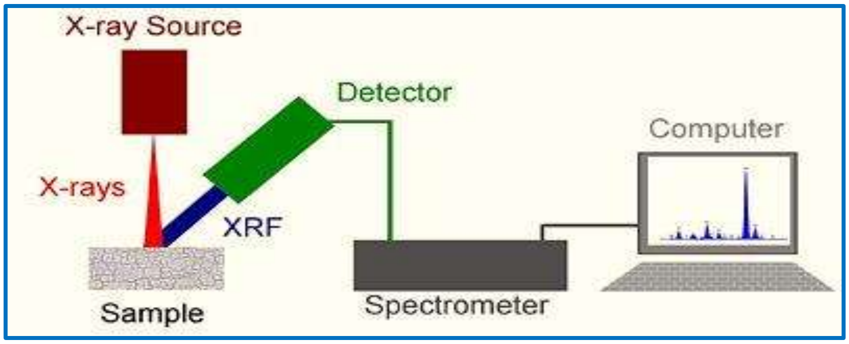
a. Atomic Absorption Spectrometer: Is a technique for determining the concentration of a particular metal element in a sample, in order to measure its chemical concentration. The atomic absorption spectroscopy can be used to analyze the concentration of over 62 different metals in a solution and mostly have 4 principal components; a light source (usually a hollow cathode lamp); an atom cell (atomizer); a monochromator and a detector, which is a read out device.

The spectrometer for analyzing chemical composition is an important tool when you need to know the composition of a metal or alloy. The qualitative chemical composition analysis of metals and alloys are identified by X-ray fluorescence spectrometry, which identifies the chemical of alloys such as: carbon steel, stainless steel, tool steel, high speed steel, cast iron, copper, zinc, aluminum, nickel, silver, titanium alloy for use in prosthesis, stainless steels used in surgical implants and other materials.



After identifying each component, it is possible to quantify the levels of the elements of a given alloy and, with the obtained results, perform your classification through the chemical composition or check whether the material meets a particular technical specification. It is possible to determine the purity of materials such as silver, copper, zinc and aluminum.

b. X-Ray Absorption Spectrometer: Is a technique that uses the synchrotron radiation to provide information about electronic, structural, and magnetic properties of certain elements in materials. This information is obtained when X-rays are absorbed by an atom at energies near and above the core level binding energies of that atom. X-Ray Absorption Spectrometer is commonly used for several disciplines, as chemistry, physics, biology, materials science, environmental science, mineralogy, etc. The data analysis could be very complex, as it involves theoretical modeling spectrum and a further comparison with the real spectra; but using standards for comparison can simplified the analysis.



6. Metallography:

Is the study of the physical structure and components of metals, typically using microscopy. The surface of a metallographic specimen is prepared by various methods of grinding, polishing, and etching. Ceramic and polymeric materials may also be prepared using metallographic techniques, hence the terms ceramography, plastography and, collectively, materialography. After preparation, it is often analyzed using optical or electron microscopy. Using only metallographic techniques, a skilled technician can identify a number of alloys and also predict their material properties. The preparation of specimens follows:

Generally, the work piece is cut to fit into a mold into which a self-curing epoxy is poured. After hardening, the specimen is polished to a mirror finish with successive grinding and polishing media. An etchant is then applied to reveal the microstructure by corroding only layers of atoms, leaving the crystallographic planes, reflected at different angles by light, revealing the microstructure when observed in an optical microscope. Metallography is an important step in evaluating whether the metal has been affected by heat, corrosion, embrittlement, defective welds, etc.

Personnel Training, Qualification and Certification:

Successful and consistent application of nondestructive testing techniques depends heavily on personnel training, experience and integrity. Personnel involved in application of industrial NDT methods and interpretation of results should be certified, and in some industrial sectors certification is enforced by law or by the applied codes and standards.

Qualification and certification procedures are in **ASNT SNT-TC-1A**. The certification is simply defined as: "Written testimony of qualification". In **EN 4179:2009**, aerospace sector, contains the following definitions.

Levels of Certification:

NDT personnel certification specifies **three "levels"** of qualification or certification, usually designated as Level 1, Level 2 and Level 3 (or Level I, II or III). The roles and responsibilities of personnel in each level are generally as follows:

a. Level 1: Are **qualified technicians,** who are able to perform only specific calibrations and tests under close supervision and direction by higher level personnel. They can only report test results. Normally they work following specific work instructions for testing procedures and rejection criteria.

b. Level 2: Are **engineers or experienced technicians**, who are able to set up and calibrate testing equipment, conduct the inspection according to codes and standards and compile work instructions for Level 1 technicians. They are also authorized to report, interpret, evaluate, record testing results, supervise and train Level 1 technicians. They also must be familiar with applicable material codes and standards and have some knowledge of the manufacture and service of tested products.

c. Level 3: Are usually **specialized engineers** or **very experienced technicians**, who are able to establish NDT techniques and procedures and interpret drawings, fabrication, codes and standards. They also direct NDT laboratories and have central role in personnel certification. They are expected to have wider knowledge about materials, manufacture and product technology.

References:

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