This article provides answers to the following questions, among others:

- What type of loads do exist?
- What is dimensioning?
- What is the primary purpose of destructive testing?
- In which cases is non-destructive testing preferable?

Materials such as steels generally have to withstand a wide variety of loads. The different types of loads can be classified as follows:

- tension
- compression
- shearing
- torsion
- bending
- buckling

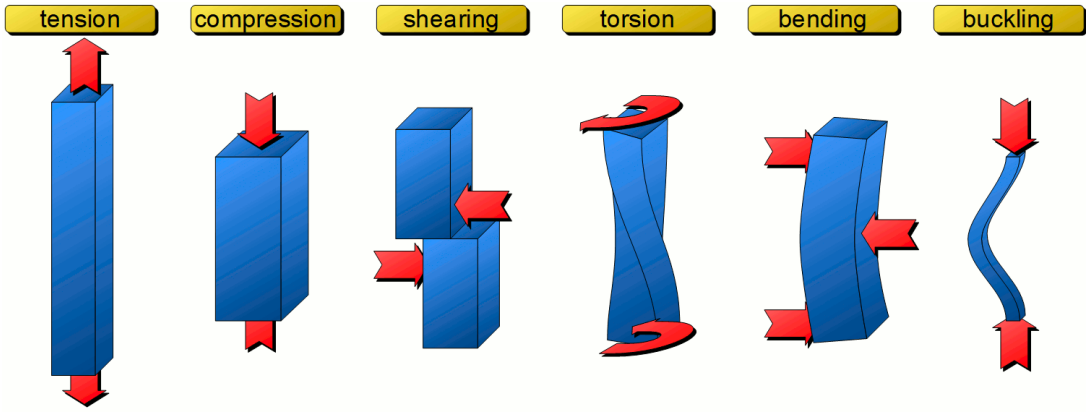



*Figure: Types of loads*

The intensity of the load can either be temporally constant or vary permanently. A constant stress intensity is also referred to as *static load*. If, on the other hand, the level of stress varies in its intensity and/or in its direction, one speaks of a *dynamic load*.

A particular type of load always has a certain temporal course. In general, several types of loads occur in combination. This is the case, for example, with a shaft driven on one side, which is simultaneously subjected to torsion, bending and shearing. Depending on whether the shaft is driven with constant torque or whether the torque changes permanently, it is a static or dynamic load. Thus, there are countless possibilities how components can be stressed.

When dimensioning components, the engineer must be able to refer to specific values that characterize the different stress limits of the materials used with respect to their temporal course. The stress limit can be based on either an unacceptable deformation or a fracture. For this reason, various materials testing methods were developed to determine the corresponding failure limits depending on the type of load and its time course.

In principle, material testing methods can be divided into two categories:

- destructive testing
- non-destructive testing.

With destructive testing, the material is damaged and the component can usually no longer be used. In general, specially prepared and standardized samples are used for this type of testing. The destructive testing procedures provide important parameters in order to determine not only the proper material but also geometry of the component depending on the applied load. The determination of the component dimensions is also referred to as *dimensioning!*

Destructive testing is used to determine specific material constants or component constants!

The following test methods are considered destructive testing and are described in more detail in the respective article

- tensile test
- compression test
- hardness test
- flexural test
- Charpy impact test
- fatigue test
- creep rupture test
- relaxation test
- cupping test

Due to the complexity and the interaction between the different loads, not all cases can be recorded in material properties. This is always a problem when human lives are at risk due to component failure. For this reason, safety-relevant components must be checked at regular intervals, as is the case with turbine blades of aircraft engines. It is not economically viable to carry out a destructive material test at this point in order to subsequently state that everything was in order.

That is why non-destructive testing (NDT) was developed. This means that the component can still be used, provided everything is fine. In this way, for example, the said turbine blades are inspected non-destructively for cracks by *ultrasonic testing* or *eddy-current testing*. Non-destructive testing also includes the visual inspection of whether a component is externally damaged or not.

The following test methods are considered non-destructive testing and are described in more detail in the respective article

- ultrasonic testing (UT)
- dye penetrant inspection (DPI)
- magnetic particle testing (MPI)
- eddy current testing (ECT)

In general no specific material constant can be derived from non-destructive testings as in destructive testing. The result is only a statement whether the component can still be used or must be repaired or even replaced.

Non-destructive testing is used to check the usability of finished components (inspection) – no material parameters are determined!

## What is NDT?

The field of Nondestructive Testing (NDT) is a very broad, interdisciplinary field that plays a critical role in assuring that structural components and systems perform their function in a reliable and cost effective fashion. NDT technicians and engineers define and implement tests that locate and characterize material conditions and flaws that might otherwise cause planes to crash, reactors to fail, trains to derail, pipelines to burst, and a variety of less visible, but equally troubling events. These tests are performed in a manner that does not affect the future usefulness of the object or material. In other words, NDT allows parts and material to be inspected and measured without damaging them. Because it allows inspection without interfering with a product's final use, NDT provides an excellent balance between quality control and cost-effectiveness. Generally speaking, NDT applies to industrial inspections. The technologies that are used in NDT are similar to those used in the medical industry, but nonliving objects are the subjects of the inspections.

## What is NDE?

Nondestructive evaluation (NDE) is a term that is often used interchangeably with NDT. However, technically, NDE is used to describe measurements that are more quantitative in nature. For example, an NDE method would not only locate a defect, but it would also be used to measure something about that defect such as its size, shape, and orientation. NDE may be used to determine material properties, such as fracture toughness, formability, and other physical characteristics.

## Some NDT/NDE Technologies:

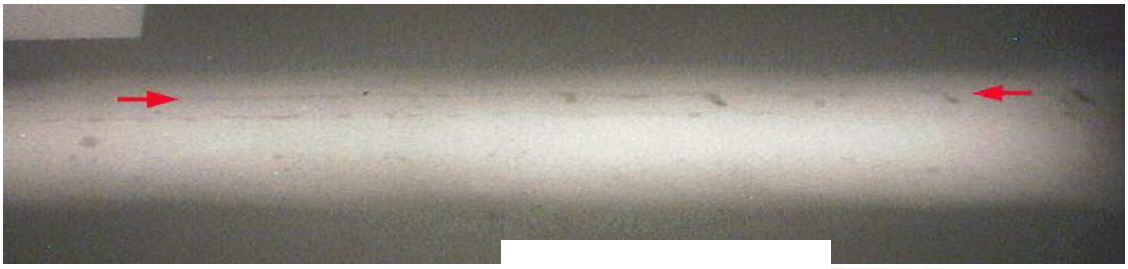
Many people are already familiar with some of the technologies that are used in NDT and NDE from their uses in the medical industry. Most people have also had an X-ray taken and many mothers have had ultrasound used by doctors to give their baby a checkup while still in the womb. X-rays and ultrasound are only a few of the technologies used in the field of NDT/NDE. The number of inspection methods seems to grow daily, but a quick summary of the most commonly used methods is provided below.

### Visual and Optical Testing (VT)

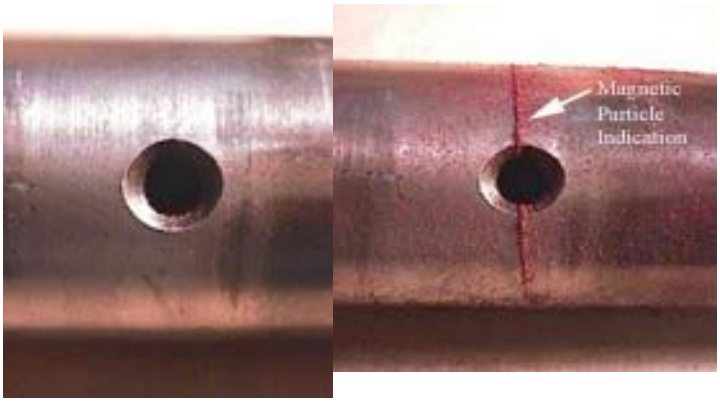
The most basic NDT method is visual examination. Visual examiners follow procedures that range from simply looking at a part to see if surface imperfections are visible, to using computer controlled camera systems to automatically recognize and measure features of a component.

### Radiography (RT)

RT involves using penetrating gamma- or X-radiation on materials and products to look for defects or examine internal or hidden features. An X-ray generator or radioactive isotope is used as the source of radiation. Radiation is directed through a part and onto film or other detector. The resulting shadowgraph shows the internal features and soundness of the part. Material thickness and density changes are indicated as lighter or darker areas on the film or detector. The darker areas in the radiograph below represent internal voids in the component.

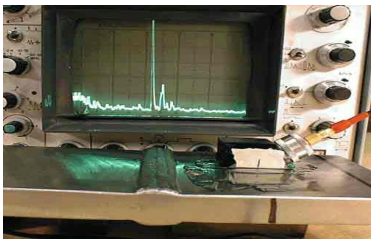


## Magnetic Particle Testing (MT)




This NDT method is accomplished by inducing a magnetic field in a ferromagnetic material and then dusting the surface with iron particles (either dry or suspended in liquid). Surface and near-surface flaws disrupt the flow of the magnetic field within the part and force some of the field to leak out at the surface. Iron particles are attracted and concentrated at sites of the magnetic flux leakages. This produces a visible indication of defect on the surface of the material. The images above demonstrate a component before and after inspection using dry magnetic particles.

## Ultrasonic Testing (UT)



In ultrasonic testing, high-frequency sound waves are transmitted into a material to detect imperfections or to locate changes in material properties. The most commonly used ultrasonic testing technique is pulse echo, whereby sound is introduced into a test object and reflections (echoes) from internal imperfections or the part's geometrical surfaces are returned to a receiver. Below is an example of shear wave weld inspection. Notice the indication extending to the upper limits of the screen. This indication is produced by sound reflected from a defect within the weld.

## Penetrant Testing (PT)

With this testing method, the test object is coated with a solution that contains a visible or fluorescent dye. Excess solution is then removed from the surface of the object but is left in surface breaking defects. A developer is then applied to draw the penetrant out of the defects. With fluorescent dyes, ultraviolet light is used to make the bleedout fluoresce brightly, thus allowing imperfections to be readily seen. With visible dyes, a vivid color contrast between the penetrant and developer makes the bleedout easy to see. The red indications in the image represent a defect in this component.

### Electromagnetic Testing (ET)

There are a number of electromagnetic testing methods but the focus here will be on eddy current testing. In eddy current testing, electrical currents (eddy currents) are generated in a conductive material by a changing magnetic field. The strength of these eddy currents can be measured. Material defects cause interruptions in the flow of the eddy currents which alert the inspector to the presence of a defect or other change in the material. Eddy currents are also affected by the electrical conductivity and magnetic permeability of a material, which makes it possible to sort some materials based on these properties. The technician in the image is inspecting an aircraft wing for defects.

### Leak Testing (LT)

Several techniques are used to detect and locate leaks in pressure containment parts, pressure vessels, and structures. Leaks can be detected by using electronic listening devices, pressure gauge measurements, liquid and gas penetrant techniques, or simple soap-bubble tests.

### Acoustic Emission Testing (AE)

When a solid material is stressed, imperfections within the material emit short bursts of acoustic energy called "emissions." As in ultrasonic testing, acoustic emissions can be detected by special receivers. Emission sources can be evaluated through the study of their intensity and arrival time to collect information (such as their location) about the sources of the energy. [1]

[1] "About NDT - NDT-ED.org." 2014. 20 Aug. 2014 <https://www.nde-ed.org/AboutNDT/aboutndt.htm>

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# Comparison of Non-Destructive Testing Methods

## Resonant Inspection Compared to Other Non-Destructive Testing Techniques

**Applications**
Below you will find a general outline of the capabilities of common nondestructive testing (NDT) methods. This is intended as brief summary of each discipline's capabilities.

**Traditional NDT Technique Comparison**

■ Excellent ▲ Fair ● Poor

| | RAM Resonant Acoustic | ET Eddy Current | MT/PT Magnetic/ Penetrant | UT Ultrasonic | RT Radiography |
|---|---|---|---|---|---|
| **Defect/Issue** | | | | | |
| Cracks/Chips/Voids | ■ | ■ | ■ | ■ | ▲ |
| Material Properties | ■ | ● | ● | ● | ▲ |
| Missed Operations | ■ | ● | ● | ● | ● |
| Structural Integrity | ■ | ■ | ■ | ■ | ■ |
| Product Lot Variation | ▲ | ▲ | ■ | ■ | ■ |
| **Defect Location** | | | | | |
| Surface (External) | ■ | ■ | ■ | ■ | ● |
| Internal | ■ | ● | ● | ■ | ■ |
| Brazing/Bonding/Welding | ■ | ● | ● | ▲ | ▲ |
| **Speed/Training/Cost** | | | | | |
| Throughput | ■ | ▲ | ▲ | ■ | ● |
| Training/Certification | ■ | ● | ● | ● | ● |
| Total Inspection Costs | ■ | ▲ | ▲ | ● | ● |
| **Automation Capacity** | | | | | |
| Quantitative Results | ■ | ● | ● | ▲ | ● |
| Ease of Automation | ■ | ▲ | ▲ | ● | ● |
| Cost of Automation | ■▲ | ▲ | ● | ● | ● |

Quick Links: Resonant Inspection (RI) Ultrasonic Testing (UT) Radiography (RT) Eddy Current (ET) Liquid Penetrant (LPI / PT) Magnetic Particle (MT / MPI) Infrared Thermography Visual Inspection (VT)

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### RESONANT INSPECTION (RI)

Resonant Inspection is a whole-body test method which detects resonant frequency shifts resulting from changes in mass, stiffness or damping of a part. Resonance can detect defects such as cracks, voids, chips, brazing problems, nodularity, variations in hardness, missed manufacturing processes, delamination, and more.

Applications include, but are not limited to, powder metal parts, castings, ductile iron parts, brazed assemblies, forgings, stampings and ceramic parts.

Non-Destructive Testing Resonant Acoustic Method (NDT-RAM) is a form of resonant inspection offered by The Modal Shop. NDT-RAM is available in automated, semi-automated, manual, and small-part drop-test systems. Learn more about which system is right for you.

**Advantages**

- Whole body test for internal and external flaws
- Fast testing time: 3 seconds per part (typical)
- No part preparation or cleaning required
- Objective pass/fail result
- No consumables expenses
- Easily automated

**Disadvantages**

- Not diagnostic - does not indicate where flaw is, just there is one
- Materials that resonate only - metal, composites and ceramic parts
- Large parts (> 100 lbs.) difficult to test

- Easily integrated into manufacturing process
- Permanent record capability
- Easily finds first n number of natural frequencies for NVH applications
- Best for high volume quality inspection
- Designed to be on the plant floor

- Significant manufacturing process variations can mask defect detection

---

**ULTRASONIC TESTING (UT)**

Measures thickness, velocity or detects internal defects and variations, such as cracks, lack of fusion, delaminations and lack of bond.

Applications include wrought metals, welds, brazed joints, adhesive or bonded joints, non-metallic materials, in-service parts.

**Advantages**

- Most sensitive to cracks
- Immediate results
- Automation possible
- Permanent record capability
- Portable
- High penetration capability

**Disadvantages**

- Couplant required
- Complex, or small parts may be difficult to check
- Defect may be missed if not in the path of the ultrasonic signal
- Reference standards required
- Trained operators for manual inspections
- Special probes
- Surface condition

---

**RADIOGRAPHY (RT)**

Measures or detects, internal defects and variations, porosity, inclusions, cracks, lack of fusion, corrosion, geometry variation, density changes, misassembled and misaligned parts.

**Advantages**

- Permanent records
- Portable
- Geometry variation does not affect direction of radiation beam

**Disadvantages**

- Radiation hazard
- Expensive
- Trained operators needed
- Linear defect may be missed
- Depth of defect not indicated
- Access to at least two sides of the part required

---

**EDDY CURRENT (ET)**

Measures or detects surface and subsurface cracks and seams, alloy content, heat treatment variations, wall and coating thickness, crack depth, conductivity and permeability.

**Advantages**

- High speed
- Low cost
- Permanent record capability
- No couplant required
- No probe contact required

**Disadvantages**

- Conductive material only
- Shallow depth of penetration
- Surface roughness may affect test quality

---

**LIQUID PENETRANT (LPI / PT)**

Measures or detects defects open to the surface of parts such as cracks, porosity, seams, laps and through wall leaks.

**Advantages**

- Low cost
- Portable
- Indications may be further examined

**Disadvantages**

- Defect must be open to the surface
- Parts must be cleaned before and after testing
- Surface films, such as coatings, scale, and smeared metal may visually mask defects

---

**MAGNETIC PARTICLE INSPECTION (MT/ MPI)**

Measures or detects surface and qualified subsurface defects, cracks, seams, porosity, inclusions, and very sensitive for locating small tight cracks.

**Advantages**

- Low cost
- Portable
- Subsurface defects

**Disadvantages**

- Ferromagnetic materials only
- Alignment of magnetic field is critical
- Demagnetization required after the test
- Surface coatings can mask defects
- Pre and post cleaning necessary
- Messy

- Subjective: dependent on operator interpretation
- Difficult to automate

---

**INFRARED THERMOGRAPHY**

Measures or detects hot spots, heat transfer, temperature ranges, temperature monitoring and electrical assemblies.

**Advantages**

- Permanent record or thermal picture
- Remote sensing
- Portable

**Disadvantages**

- Expensive
- Reference standards required
- Poor resolution on thick sections

---

**VISUAL TESTING (VT)**

Measures or detects surface flaws, blemishes, missing features, and dimensional flaws.

**Advantages**

- Generally fast test time
- Can be automated
- Good at finding dimensional flaws or surface blemishes
- Portable

**Disadvantages**

- Reference standards required
- May require multiple cameras and viewing angles for automated systems
- Subject to operator interpretation if not automated

---

**Learn More**

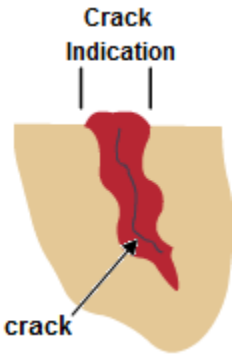
• What is Non-Destructive Testing?
• Resonant Acoustic Method
• How the Equipment Works
• Measurement and Detection Principles
• Advantages of NDT-RAM™
• Case Studies

Back to NDT

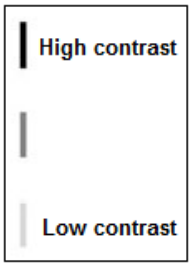
# Liquid Penetrant Testing

Liquid penetrant testing is one of the oldest and simplest NDT methods where its earliest versions (*using kerosene and oil mixture*) dates back to the 19th century. This method is used to reveal surface discontinuities by bleedout of a colored or fluorescent dye from the flaw. The technique is based on the ability of a liquid to be drawn into a "clean" surface discontinuity by capillary action. After a period of time called the "dwell time", excess surface penetrant is removed and a developer applied. This acts as a blotter that draws the penetrant from the discontinuity to reveal its presence.

The advantage that a liquid penetrant inspection offers over an unaided visual inspection is that it makes defects easier to see for the inspector where that is done in two ways:




- It produces a flaw indication that is much larger and easier for the eye to detect than the flaw itself. Many flaws are so small or narrow that they are undetectable by the unaided eye (*a person with a perfect vision can not resolve features smaller than 0.08 mm*).
- It improves the detectability of a flaw due to the high level of contrast between the indication and the background which helps to make the indication more easily seen (*such as a red indication on a white background for visable penetrant or a penetrant that glows under ultraviolate light for flourecent penetrant*).




Liquid penetrant testing is one of the most widely used NDT methods. Its popularity can be attributed to two main factors: its relative ease of use and its flexibility. It can be used to inspect almost any material provided that its surface is not extremely rough or porous. Materials that are commonly inspected using this method include; metals, glass, many ceramic materials, rubber and plastics.

However, liquid penetrant testing can only be used to inspect for flaws that break the surface of the sample (*such as surface cracks, porosity, laps, seams, lack of fusion, etc.*).

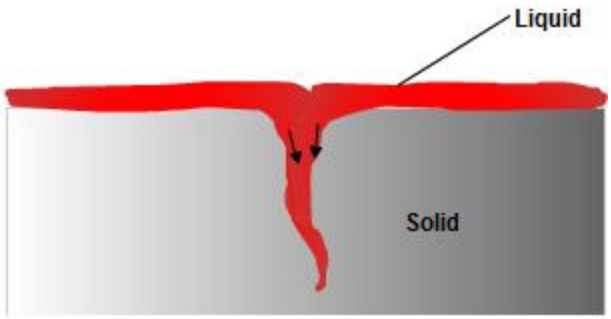
## Steps of Liquid Penetrant Testing

The exact procedure for liquid penetrant testing can vary from case to case depending on several factors such as the penetrant system being used, the size and material of the component being inspected, the type of discontinuities being expected in the component and the condition and environment under which the inspection is performed. However, the general steps can be summarized as follows:

1. *Surface Preparation*: One of the most critical steps of a liquid penetrant testing is the surface preparation. The surface must be free of oil, grease, water, or other contaminants that may prevent penetrant from entering flaws. The sample may also require etching if mechanical operations such as machining, sanding, or grit blasting have been performed. These and other mechanical operations can smear metal over the flaw opening and prevent the penetrant from entering.

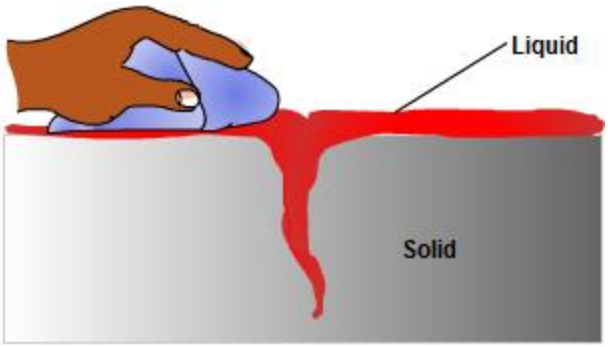
2. *Penetrant Application*: Once the surface has been thoroughly cleaned and dried, the penetrant material is applied by spraying, brushing, or immersing the part in a penetrant bath.

3. *Penetrant Dwell*: The penetrant is left on the surface for a sufficient time to allow as much penetrant as possible to be drawn or to seep into a defect. Penetrant dwell time is the total time that the penetrant is in contact with the part surface. Dwell times are usually recommended by the penetrant producers or required by the specification being followed. The times vary depending on the application, penetrant materials used, the material, the form of the material being inspected, and the type of discontinuity being inspected for. Minimum dwell times typically range from 5 to 60 minutes. Generally, there is no harm in using a longer penetrant dwell time as long as the penetrant is not allowed to dry. The ideal dwell time is often determined by experimentation and may be very specific to a particular application.



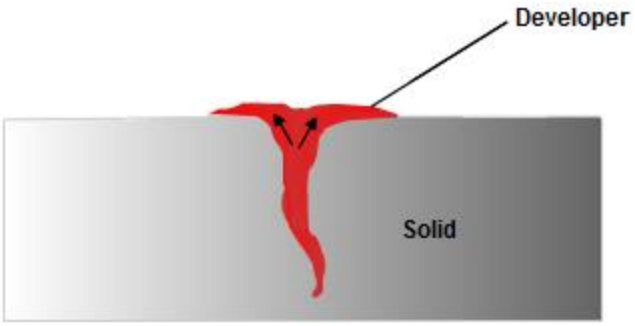

4. *Excess Penetrant Removal*: This is the most delicate step of the inspection procedure because the excess penetrant must be removed from the surface of the sample while removing as little penetrant as possible from defects.

Depending on the penetrant system used, this step may involve cleaning with a solvent, direct rinsing with water, or first treating the part with an emulsifier and then rinsing with water.




5. *Developer Application*: A thin layer of developer is then applied to the sample to draw penetrant trapped in flaws back to the surface where it will be visible. Developers come in a variety of forms that may be applied by dusting (*dry powders*), dipping, or spraying (*wet developers*).

6. *Indication Development*: The developer is allowed to stand on the part surface for a period of time sufficient to permit the extraction of the trapped penetrant out of any surface flaws. This development time is usually a minimum of 10 minutes. Significantly longer times may be necessary for tight cracks.




7. *Inspection*: Inspection is then performed under appropriate lighting to detect indications from any flaws which may be present.

8. *Clean Surface*: The final step in the process is to thoroughly clean the part surface to remove the developer from the parts that were found to be acceptable.

## Advantages and Disadvantages

The primary advantages and disadvantages when compared to other NDT methods are:

*Advantages*

- High sensitivity (*small discontinuities can be detected*).

- Few material limitations (*metallic and nonmetallic, magnetic and nonmagnetic, and conductive and nonconductive materials may be inspected*).
- Rapid inspection of large areas and volumes.
- Suitable for parts with complex shapes.
- Indications are produced directly on the surface of the part and constitute a visual representation of the flaw.
- Portable (materials are available in aerosol spray cans)
- Low cost (materials and associated equipment are relatively inexpensive)

*Disadvantages*

- Only surface breaking defects can be detected.
- Only materials with a relatively nonporous surface can be inspected.
- Pre-cleaning is critical since contaminants can mask defects.
- Metal smearing from machining, grinding, and grit or vapor blasting must be removed.
- The inspector must have direct access to the surface being inspected.
- Surface finish and roughness can affect inspection sensitivity.
- Multiple process operations must be performed and controlled.
- Post cleaning of acceptable parts or materials is required.
- Chemical handling and proper disposal is required.

## Penetrants

Penetrants are carefully formulated to produce the level of sensitivity desired by the inspector. The penetrant must possess a number of important characteristics:

- spread easily over the surface of the material being inspected to provide complete and even coverage.
- be drawn into surface breaking defects by capillary action.
- remain in the defect but remove easily from the surface of the part.
- remain fluid so it can be drawn back to the surface of the part through the drying and developing steps.
- be highly visible or fluoresce brightly to produce easy to see indications.
- not be harmful to the material being tested or the inspector.

Penetrant materials are not designed to perform the same. Penetrant manufactures have developed different formulations to address a variety of inspection applications. Some applications call for the detection of the smallest defects possible while in other applications, the rejectable defect size may be larger. The penetrants that are used to detect the smallest defects will also produce the largest amount of irrelevant indications.

Standard specifications classify penetrant materials according to their physical characteristics and their performance.

- Penetrant materials come in two basic types:

  ***Type 1 - Fluorescent Penetrants***: they contain a dye or several dyes that fluoresce when exposed to ultraviolet radiation.

  ***Type 2 - Visible Penetrants***: they contain a red dye that provides high contrast against the white developer background.

  Fluorescent penetrant systems are more sensitive than visible penetrant systems because the eye is drawn to the glow of the fluorescing indication. However, visible penetrants do not require a darkened area and an ultraviolet light in order to make an inspection.

- Penetrants are then classified by the method used to remove the excess penetrant from the part. The four methods are:

  ***Method A - Water Washable***: penetrants can be removed from the part by rinsing with water alone. These penetrants contain an emulsifying agent (detergent) that makes it possible to wash the penetrant from the part surface with water alone. Water washable penetrants are sometimes referred to as self-emulsifying systems.

  ***Method B - Post-Emulsifiable, Lipophilic***: the penetrant is oil soluble and interacts with the oil-based emulsifier to make removal possible.

  ***Method C - Solvent Removable***: they require the use of a solvent to remove the penetrant from the part.

  ***Method D - Post-Emulsifiable, Hydrophilic***: they use an emulsifier that is a water soluble detergent which lifts the excess penetrant from the surface of the part with a water wash.

- Penetrants are then classified based on the strength or detectability of the indication that is produced for a number of very small and tight fatigue cracks. The five sensitivity levels are:

  ***Level ½ - Ultra Low Sensitivity***

  ***Level 1 - Low Sensitivity***

  ***Level 2 - Medium Sensitivity***

  ***Level 3 - High Sensitivity***

  ***Level 4 - Ultra-High Sensitivity***

  The procedure for classifying penetrants into one of the five sensitivity levels uses specimens with small surface fatigue cracks. The brightness of the indication produced is measured using a photometer.

## Developers

The role of the developer is to pull the trapped penetrant material out of defects and spread it out on the surface of the part so it can be seen by an inspector. Developers used with visible penetrants create a white background so there is a greater degree of contrast between the indication and the surrounding background. On the other hand, developers used with fluorescent penetrants both reflect and refract the incident ultraviolet light, allowing more of it to interact with the penetrant, causing more efficient fluorescence.

According to standards, developers are classified based on the method that the developer is applied (*as a dry powder, or dissolved or suspended in a liquid carrier*). The six standard forms of developers are:

***Form a - Dry Powder***

***Form b - Water Soluble***

***Form c - Water Suspendable***

***Form d - Nonaqueous Type 1: Fluorescent (Solvent Based)***

***Form e - Nonaqueous Type 2: Visible Dye (Solvent Based)***

***Form f - Special Applications***

### *Dry Powder*

Dry powder developers are generally considered to be the least sensitive but they are inexpensive to use and easy to apply. Dry developers are white, fluffy powders that can be applied to a thoroughly dry surface in a number of ways; by dipping parts in a container of developer, by using a puffer to dust parts with the developer, or placing parts in a dust cabinet where the developer is blown around. Since the powder only sticks to areas of indications since they are wet, powder developers are seldom used for visible inspections.

### *Water Soluble*

As the name implies, water soluble developers consist of a group of chemicals that are dissolved in water and form a developer layer when the water is evaporated away. The best method for applying water soluble developers is by spraying it on the part. The part can be wet or dry. Dipping, pouring, or brushing the solution on to the surface is sometimes used but these methods are less desirable. Drying is achieved by placing the wet, but well drained part, in a recirculating warm air dryer with a temperature of 21°C. Properly developed parts will have an even, light white coating over the entire surface.

### *Water Suspendable*

Water suspendable developers consist of insoluble developer particles suspended in water. Water suspendable developers require frequent stirring or agitation to keep the particles from settling out of suspension. Water suspendable developers are applied to parts in the same manner as water soluble developers then the parts are dried using warm air.

### *Nonaqueous*

Nonaqueous developers suspend the developer in a volatile solvent and are typically applied with a spray gun. Nonaqueous developers are commonly distributed in aerosol spray cans for portability. The solvent tends to pull penetrant from the indications by solvent action. Since the solvent is highly volatile, forced drying is not required.

### *Special Applications*

Plastic or lacquer developers are special developers that are primarily used when a permanent record of the inspection is required.

## Preparation of Part

One of the most critical steps in the penetrant inspection process is preparing the part for inspection. All coatings, such as paints, varnishes, plating, and heavy oxides must be removed to ensure that defects are open to the surface of the part. If the parts have been machined, sanded, or blasted prior to the penetrant inspection, it is possible that a thin layer of metal may have smeared across the surface and closed off defects. Also, some cleaning operations, such as steam cleaning, can cause metal smearing in softer materials. This layer of metal smearing must be removed before inspection.

## Penetrant Application and Dwell Time

The penetrant material can be applied in a number of different ways, including spraying, brushing, or immersing the parts in a penetrant bath. Once the part is covered with penetrant it must be allowed to dwell so the penetrant has time to enter any defect that is present.

There are basically two dwell mode options:

- *Immersion-dwell*: keeping the part immersed in the penetrant during the dwell period.
- *Drain-dwell*: letting the part drain during the dwell period (*this method gives better sensitivity*).

***Penetrant Dwell Time***

Penetrant dwell time is the total time that the penetrant is in contact with the part surface. The dwell time is important because it allows the penetrant the time necessary to seep or be drawn into a defect. Dwell times are usually recommended by the penetrant producers or required by the specification being followed. The time required to fill a flaw depends on a number of variables which include:

- The surface tension of the penetrant.
- The contact angle of the penetrant.
- The dynamic shear viscosity of the penetrant.
- The atmospheric pressure at the flaw opening.
- The capillary pressure at the flaw opening.
- The pressure of the gas trapped in the flaw by the penetrant.

- The radius of the flaw or the distance between the flaw walls.
- The density or specific gravity of the penetrant.
- Microstructural properties of the penetrant.

The ideal dwell time is often determined by experimentation and is often very specific to a particular application. For example, the table shows the dwell time requirements for steel parts according to some of the commonly used specifications.

**Steel:**

| Source: | Form: | Discontinuity: | Dwell Time for Water Washable (minutes) | Dwell Time for Post Emulsifiable (minutes) |
|---|---|---|---|---|
| Military Technical Order 33B-1-1 | Castings | Porosity | 5 to 10 | 10 |
| | | Cold Shuts | 5 to 15 | 10 |
| | Extrusions/Forgings | Laps | *NR | 10 |
| | Welds | Lack of Fusion | 30 | 20 |
| | | Porosity | 30 | 20 |
| | All | Cracks | 30 | 20 |
| | All | Fatigue Cracks | *NR | 30 |
| ASME Boiler and Pressure Vessel Code | Castings | Porosity | 30 | |
| | | Cold Shuts | 30 | |
| | Extrusions/Forgings | Laps | 60 | |
| | Welds | Lack of Fusion | 60 | |
| | | Porosity | 60 | |
| | All | Cracks | 30 | |
| ASTM E-1209/ E-1210 | Castings | Porosity | 5 | 5 |
| | | Cold Shuts | 5 | 5 |
| | Extrusions/Forgings/ and Plate | Laps/Cracks | 10 | 10 |
| | Welds | Lack of Fusion | 5 | 5 |
| | | Porosity | 5 | 5 |
| | All | Cracks | 5 | 5 |

*NR: Not a recommended method of evaluation.

## Penetrant Removal Process

The penetrant removal procedure must effectively remove the penetrant from the surface of the part without removing an appreciable amount of entrapped penetrant from the discontinuity. If the removal process extracts penetrant from the flaw, the flaw indication will be reduced by a proportional amount. If the penetrant is not effectively removed from the part surface, the contrast between the indication and the background will be reduced.

### *Removal Method*

As mentioned previously, penetrant systems are classified into four categories according to the method used for excess penetrant removal.

- *Method A: Water-Washable*
- *Method B: Post-Emulsifiable, Lipophilic*
- *Method C: Solvent Removable*
- *Method D: Post-Emulsifiable, Hydrophilic*

Method C, Solvent Removable, is used primarily for inspecting small localized areas. This method requires hand wiping the surface with a cloth moistened with the solvent remover, and is, therefore, too labor intensive for most production situations.

Method A, Water-Washable, is the most economical to apply of the different methods and it is easy to use. Water-washable or self-emulsifiable penetrants contain an emulsifier as an integral part of the formulation. The excess penetrant may be removed from the object surface with a simple water rinse.

When removal of the penetrant from the defect due to over-washing of the part is a concern, a post-emulsifiable penetrant system can be used. The post-emulsifiable methods are generally only used when very high sensitivity is needed. Post-emulsifiable penetrants require a separate emulsifier to breakdown the penetrant and make it water washable. The part is usually immersed in the emulsifier but hydrophilic emulsifiers may also be sprayed on the object. Brushing the emulsifier on to the part is not recommended because the bristles of the brush may force emulsifier into discontinuities, causing the entrapped penetrant to be removed. The emulsifier is allowed sufficient time to react with the penetrant on the surface of the part but not given time to make its way into defects to react with the trapped penetrant. Controlling the reaction time is of essential importance when using a post-emulsifiable system. If the emulsification time is too short, an excessive amount of penetrant will be left on the surface, leading to high background levels. If the emulsification time is too long, the emulsifier will react with the penetrant entrapped in discontinuities, making it possible to deplete the amount needed to form an indication.

The hydrophilic post-emulsifiable method (*Method D*) is gives better sensitivity than the lipophilic post-emulsifiable method (*Method B*). The major advantage of hydrophilic emulsifiers is that they are less sensitive to variation in the contact and removal time.

When a post-emulsifiable penetrant is used, the penetrant inspection process includes the following steps (*extra steps are underlined*): **1**. pre-clean part, **2**. apply penetrant and allow to dwell, **3**. *pre-rinse to remove first layer of penetrant*, **4**. *apply hydrophilic emulsifier and allow contact for specified time*, **5**. rinse to remove excess penetrant, **6**. dry part, **7**. apply developer and allow part to develop, and **8**. inspect.

### *Rinse Method and Time for Water-Washable Penetrants*

The method used to rinse the excess penetrant from the object surface and the time of the rinse should be controlled so as to prevent over-washing. It is generally recommended that a coarse spray rinse or an air-agitated, immersion wash tank be

used. When a spray is being used, it should be directed at a 45° angle to the part surface so as to not force water directly into any discontinuities that may be present. The spray or immersion time should be kept to a minimum through frequent inspections of the remaining background level.

***Hand Wiping of Solvent Removable Penetrants***

When a solvent removable penetrant is used, care must also be taken to carefully remove the penetrant from the part surface while removing as little as possible from the flaw. The first step in this cleaning procedure is to dry wipe the surface of the part in one direction using a white, lint-free, cotton rag. One dry pass in one direction is all that should be used to remove as much penetrant as possible. Next, the surface should be wiped with one pass in one direction with a rag moistened with cleaner. One dry pass followed by one damp pass is all that is recommended. Additional wiping may sometimes be necessary; but keep in mind that with every additional wipe, some of the entrapped penetrant will be removed and inspection sensitivity will be reduced.

## Use and Selection of a Developer

The use of developer is almost always recommended. The output from a fluorescent penetrant is improved significantly when a suitable powder developer is used. Also, the use of developer can have a dramatic effect on the probability of detection of an inspection.

Nonaqueous developers are generally recognized as the most sensitive when properly applied. However, if the thickness of the coating becomes too great, defects can be masked. The relative sensitivities of developers and application techniques as ranked in *Volume II of the Nondestructive Testing Handbook* are shown in the table below.

| Ranking | Developer Form | Method of Application |
|---|---|---|
| 1 | Nonaqueous, Wet Solvent | Spray |
| 2 | Plastic Film | Spray |
| 3 | Water-Soluble | Spray |
| 4 | Water-Suspendable | Spray |
| 5 | Water-Soluble | Immersion |
| 6 | Water-Suspendable | Immersion |
| 7 | Dry | Dust Cloud (Electrostatic) |
| 8 | Dry | Fluidized Bed |
| 9 | Dry | Dust Cloud (Air Agitation) |
| 10 | Dry | Immersion (Dip) |

The following table lists the main advantages and disadvantages of the various developer types.

| Developer | Advantages | Disadvantages |
|---|---|---|
| **Dry** | Indications tend to remain brighter and more distinct over time<br><br>Easy to apply | Does not form contrast background so cannot be used with visible systems<br><br>Difficult to assure entire part surface has been coated |
| **Soluble** | Ease of coating entire part | Coating is translucent and provides poor contrast (*not recommended for visable systems*)<br><br>Indications for water washable systems are dim and blurred |
| **Suspendable** | Ease of coating entire part<br><br>Indications are bright and sharp<br><br>White coating of good contrast can be produced which work well for both visible and fluorescent systems | Indications weaken and become diffused after time |
| **Nonaqueous** | Very portable<br><br>Easy to apply to readily accessible surfaces<br><br>White coating of good contrast can be produced which work well for both visible and fluorescent systems<br><br>Indications show-up rapidly and are well defined<br><br>Provides highest sensitivity | Difficult to apply evenly to all surfaces<br><br>More difficult to clean part after inspection |

## Quality & Process Control

Quality control of the penetrant inspection process is essential to get good and consistent results. Since several steps and materials are involved in the inspection process, there are quality control procedures for each of them.

### *Temperature Control*

The temperature of the penetrant materials and the part being inspected can have an effect on the results. Temperatures from 27 to 49°C are reported in the literature to produce optimal results. Many specifications allow testing in the range of 4 to 52°C. Raising the temperature beyond this level will significantly raise the speed of evaporation of penetrants causing them to dry out quickly.

Since the surface tension of most materials decrease as the temperature increases, raising the temperature of the penetrant will increase the wetting of the surface and the capillary forces. Of course, the opposite is also true, so lowering the temperature will have a negative effect on the flow characteristics.

### *Penetrant Quality Control*

The quality of a penetrant inspection is highly dependent on the quality of the penetrant materials used. Only products meeting the requirements of an industry specification, such as AMS 2644, should be used. Deterioration of new penetrants primarily results from aging and contamination. Virtually all organic dyes deteriorate over time, resulting in a loss of color or fluorescent response, but deterioration can be slowed with proper storage. When possible, keep the materials in a closed container and protect from freezing and exposure to high heat.

Contamination can occur during storage and use. Of course, open tank systems are much more susceptible to contamination than are spray systems. Regular checks must be performed to ensure that the material performance has not degraded. When the penetrant is first received from the manufacturer, a sample of the fresh solution should be collected and stored as a standard for future comparison. The standard specimen should be stored in a sealed, opaque glass or metal container. Penetrants that are in-use should be compared regularly to the standard specimen to detect any changes in properties or performance.

### *Dwell Quality Control*

Dwell times are usually recommended by the penetrant producer or required by the specification being followed. The only real quality control required in the dwell step of the process is to ensure that a minimum dwell time is reached. There is no harm in allowing a penetrant to dwell longer than the minimum time as long as the penetrant is not allowed to dry on the part.

### *Emulsifier Bath Quality Control*

Quality control of the emulsifier bath is important and it should be performed per the requirements of the applicable specification.

#### *Lipophilic Emulsifiers*

Lipophilic emulsifiers mix with penetrants but when the concentration of penetrant contamination in the emulsifier becomes too great, the mixture will not function effectively as a remover. Standards require that lipophilic emulsifiers be capable of 20% penetrant contamination without a reduction in performance. When the cleaning action of the emulsifier becomes less than that of new material, it should be replaced.

#### *Hydrophilic Emulsifiers*

Hydrophilic emulsifiers have less tolerance for penetrant contamination. The penetrant tolerance varies with emulsifier concentration and the type of contaminating penetrant. In some cases, as little as 1% (by volume) penetrant contamination can seriously affect the performance of an emulsifier.

#### *Emulsifier Concentration and Contact Time*

The optimal emulsifier contact time is dependent on a number of variables that include the emulsifier used, the emulsifier concentration, the surface roughness of the part being inspected, and other factors. Usually some experimentation is required to select the proper emulsifier contact time.

### *Wash Quality Control*

The wash temperature, pressure and time are three parameters that are typically controlled in penetrant inspection process specification. A coarse spray or an immersion wash tank with air agitation is often used. When the spray method is used, the water pressure is usually limited to *276 kPa*. The temperature range of the water is

usually specified as a wide range (e.g., *10 to 38°C*). The wash time should only be as long as necessary to decrease the background to an acceptable level. Frequent visual checks of the part should be made to determine when the part has been adequately rinsed.

### *Drying Process Quality Control*

The temperature used to dry parts after the application of an aqueous wet developer or prior to the application of a dry powder or a nonaqueous wet developer, must be controlled to prevent drying in the penetrant in the flaw. To prevent harming the penetrant material, drying temperature should be kept to less than 71°C. Also, the drying time should be limited to the minimum length necessary to thoroughly dry the component being inspected.

### *Developer Quality Control*

The function of the developer is very important in a penetrant inspection. In order to accomplish its functions, a developer must adhere to the part surface and result in a uniform, highly porous layer with many paths for the penetrant to be moved due to capillary action. Developers are either applied wet or dry, but the desired end result is always a uniform, highly porous, surface layer. Since the quality control requirements for each of the developer types is slightly different, they will be covered individually.

*Dry Powder Developer*

A dry powder developer should be checked daily to ensure that it is fluffy and not caked. It should be similar to fresh powdered sugar and not granulated like powdered soap. It should also be relatively free from specks of fluorescent penetrant material from previous inspection. This check is performed by spreading a sample of the developer out and examining it under UV light.

When using the developer, a light coat is applied by immersing the test component or dusting the surface. After the development time, excessive powder can be removed by gently blowing on the surface with air not exceeding *35 kPa*.

*Wet Soluble/Suspendable Developer*

Wet soluble developer must be completely dissolved in the water and wet suspendable developer must be thoroughly mixed prior to application. The concentration of powder in the carrier solution must be controlled in these developers.

The concentration should be checked at least weekly using a hydrometer to make sure it meets the manufacturer's specification. To check for contamination, the solution should be examined weekly using both white light and UV light. Some specifications require that a clean aluminum panel be dipped in the developer, dried, and examined for indications of contamination by fluorescent penetrant materials.

These developers are applied by spraying, flowing or immersing the component. They should never be applied with a brush. Care should be taken to avoid a heavy accumulation of the developer solution in crevices and recesses.

*Solvent Suspendable*

Solvent suspendable developers are typically supplied in sealed aerosol spray cans. Since the developer solution is in a sealed vessel, direct check of the solution is not possible. However, the way that the developer is dispensed must be monitored. The spray developer should produce a fine, even coating on the surface of the part. Make sure the can is well shaken and apply a thin coating to a test article. If the spray produces spatters or an uneven coating, the can should be discarded.

When applying a solvent suspendable developer, it is up to the inspector to control the thickness of the coating. With a visible penetrant system, the developer coating must be thick enough to provide a white contrasting background but not heavy enough to mask indications. When using a fluorescent penetrant system, a very light coating should be used. The developer should be applied under white light and should appear evenly transparent.

*Development Time*

Parts should be allowed to develop for a minimum of 10 minutes and no more than 2 hours before inspecting.

### *Lighting Quality Control*

Proper lighting is of great importance when visually inspecting a surface for a penetrant indication. Obviously, the lighting requirements are different for an inspection conducted using a visible dye penetrant than they are for an inspection conducted using a fluorescent dye penetrant.

*Lighting for Visible Dye Penetrant Inspections*

When using a visible penetrant, the intensity of the white light is of principal importance. Inspections can be conducted using natural lighting or artificial lighting.

However, since natural daylight changes from time to time, the use of artificial lighting is recommended to get better uniformity. Artificial lighting should be white whenever possible (halogen lamps are most commonly used). The light intensity is required to be *100 foot-candles* (*1076 lux*) at the surface being inspected.

*Lighting for Fluorescent Penetrant Inspections*

Fluorescent penetrant dyes are excited by UV light of 365nm wavelength and emit visible light somewhere in the green-yellow range between 520 and 580nm. The source of ultraviolet light is often a mercury arc lamp with a filter. The lamps emit many wavelengths and a filter is used to remove all but the UV and a small amount of visible light between 310 and 410nm. Visible light of wavelengths above 410nm interferes with contrast, and UV emissions below 310nm include some hazardous wavelengths.

Standards and procedures require verification of filter condition and light intensity. The black light filter should be clean and the light should never be used with a cracked filter. Most UV light must be warmed up prior to use and should be on for at least *15 minutes* before beginning an inspection. Since fluorescence brightness is linear with respect to ultraviolet excitation, a change in the intensity of the light (from age or damage) and a change in the distance of the light source from the surface being inspected will have a direct impact on the inspection. For UV lights used in component evaluations, the normally accepted intensity is *1000 $\mu W/cm^2$* at *38cm* distance from the filter face. The required check should be performed when a new bulb is installed, at startup of the inspection cycle, if a change in intensity is noticed, or every eight hours of continuous use.

When performing a fluorescent penetrant inspection, it is important to keep white light to a minimum as it will significantly reduce the inspector's ability to detect fluorescent indications. Light levels of less than *2 foot-candles* (*22 lux*) are required by most procedures. When checking black light intensity a reading of the white light produced by the black light may be required to verify white light is being removed by the filter.

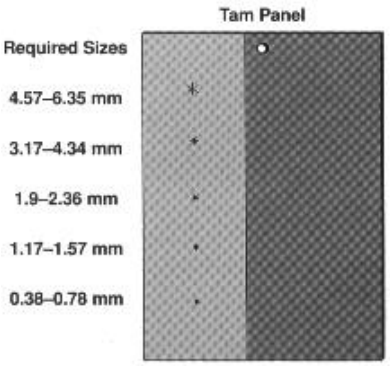
*Light Measurement*

Light intensity measurements are made using a radiometer (*an instrument that transfers light energy into an electrical current*). Some radiometers have the ability to measure both black and white light, while others require a separate sensor for each measurement. Whichever type is used, the sensing area should be clean and free of any materials that could reduce or obstruct light reaching the sensor. Radiometers are

relatively unstable instruments and readings often change considerably over time. Therefore, they should be calibrated at least every six months.

### *System Performance Check*

A system performance check is typically required daily, at the reactivation of a system after maintenance or repairs, or any time the system is suspected of being out of control. System performance checks involve processing a test specimen with known defects to determine if the process will reveal discontinuities of the size required. The specimen must be processed following the same procedure used to process production parts. The ideal specimen is a production item that has natural defects of the minimum acceptable size. As with penetrant inspections in general, results are directly dependent on the skill of the operator and, therefore, each operator should process a test specimen.



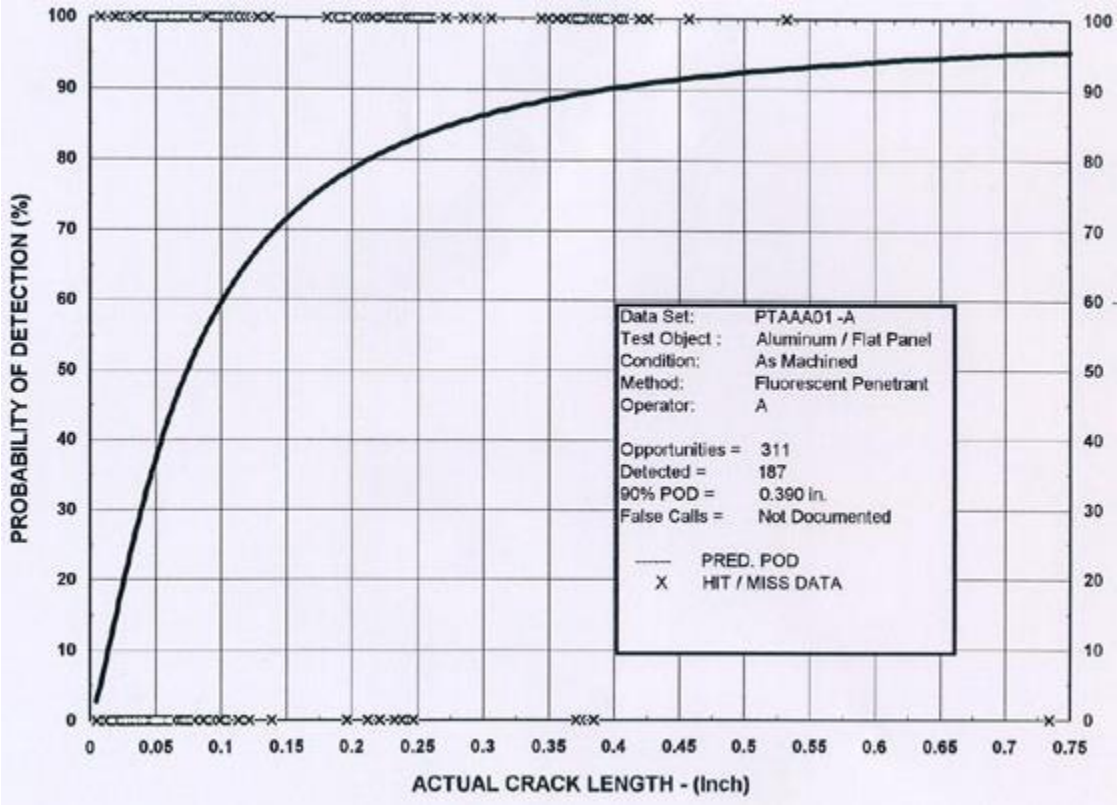

There are some universal test specimens that can be used if a reference part is not available. The most commonly used test specimen is the *TAM* or *PSM* panel which is used for fluorescent penetrant systems. These panels are usually made of stainless steel that has been chrome plated on one half and surfaced finished on the other half to produce the desired roughness. The chrome plated section is impacted from the back side to produce a starburst set of cracks in the chrome. There are five impacted areas with a range of different crack sizes corresponding to the five levels of sensitivity.

Care of system performance check specimens is critical. Specimens should be handled carefully to avoid damage. They should be cleaned thoroughly between uses and storage in a solvent is generally recommended. Before processing a specimen, it should be inspected under UV light to make sure that it is clean and not already producing an indication.

## Nature of the Defect

The nature of the defect can have a large effect on sensitivity of a liquid penetrant inspection. Sensitivity is defined as the smallest defect that can be detected with a high degree of reliability. Typically, the crack length at the sample surface is used to define

size of the defect. However, the crack length alone does not determine whether a flaw will be seen or go undetected. The volume of the defect is likely to be the more important feature. The flaw must be of sufficient volume so that enough penetrant will bleed back out to a size that is detectable by the eye or that will satisfy the dimensional thresholds of fluorescence. The figure shows an example of fluorescent penetrant inspection probability of detection (*POD*) curve as a function of crack length.




In general, penetrant testing is more effective at finding:

- Small round defects than small linear defects.
- Deeper flaws than shallow flaws.
- Flaws with a narrow opening at the surface than wide open flaws.
- Flaws on smooth surfaces than on rough surfaces.
- Flaws with rough fracture surfaces than smooth fracture surfaces.
- Flaws under tensile or no loading than flaws under compression loading.

## Health and Safety Precautions

When proper health and safety precautions are followed, liquid penetrant inspection operations can be completed without harm to inspection personnel. However, there is a number of health and safety related issues that need to be taken in consideration. The most common of those are discussed here.

### *Chemical Safety*

Whenever chemicals must be handled, certain precautions must be taken. Before working with a chemical of any kind, it is highly recommended that the material safety data sheets (MSDS) be reviewed so that proper chemical safety and hygiene practices can be followed. Some of the penetrant materials are flammable and, therefore, should be used and stored in small quantities. They should only be used in a well ventilated area and ignition sources avoided. Eye protection should always be worn to prevent contact of the chemicals with the eyes. Gloves and other protective clothing should be worn to limit contact with the chemicals.

### *Ultraviolet Light Safety*

Ultraviolet (UV) light has wavelengths ranging from 180 to 400 nanometers. These wavelengths place UV light in the invisible part of the electromagnetic spectrum between visible light and X-rays. The most familiar source of UV radiation is the sun and it is necessary in small doses for certain chemical processes to occur in the body. However, too much exposure can be harmful to the skin and eyes. The greatest threat with UV light exposure is that the individual is generally unaware that the damage is occurring. There is usually no pain associated with the injury until several hours after the exposure. Skin and eye damage occurs at wavelengths around 320 nm and shorter, which is well below the 365 nm wavelength where penetrants are designed to fluoresce. Therefore, UV lamps sold for use in penetrant testing are almost always filtered to remove the harmful UV wavelengths. The lamps produce radiation at the harmful wavelengths, so it is essential that they be used with the proper filter in place and in good condition.

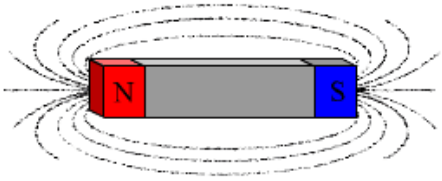
# Magnetic Particle Testing

Magnetic particle testing is one of the most widely utilized NDT methods since it is fast and relatively easy to apply and part surface preparation is not as critical as it is for some other methods. This mithod uses magnetic fields and small magnetic particles (*i.e.iron filings*) to detect flaws in components. The only requirement from an inspectability standpoint is that the component being inspected must be made of a ferromagnetic material (*a materials that can be magnetized*) such as iron, nickel, cobalt, or some of their alloys.

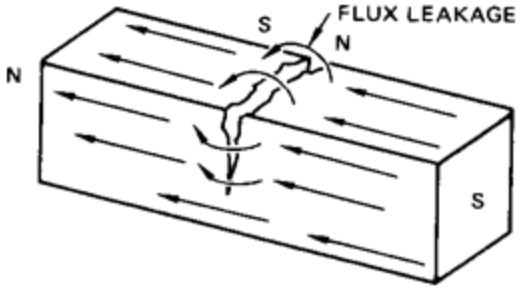
The method is used to inspect a variety of product forms including castings, forgings, and weldments. Many different industries use magnetic particle inspection such as structural steel, automotive, petrochemical, power generation, and aerospace industries. Underwater inspection is another area where magnetic particle inspection may be used to test items such as offshore structures and underwater pipelines.

## Basic Principles

In theory, magnetic particle testing has a relatively simple concept. It can be considered as a combination of two nondestructive testing methods: magnetic flux leakage testing and visual testing. For the case of a bar magnet, the magnetic field is in and around the magnet. Any place that a magnetic line of force exits or enters the magnet is called a "pole" (*magnetic lines of force exit the magnet from north pole and enter from the south pole*).

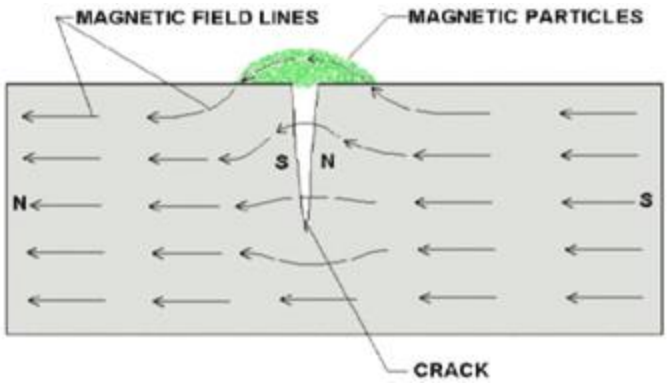



When a bar magnet is broken in the center of its length, two complete bar magnets with magnetic poles on each end of each piece will result. If the magnet is just cracked but not broken completely in two, a north and south pole will form at each edge of the crack. The magnetic field exits the north pole and reenters at the south pole. The magnetic field spreads out when it encounters the small air gap created by the crack because the air cannot support as much magnetic field per unit volume as the magnet can. When the field spreads out, it appears to leak out of the material and, thus is called a flux leakage field.



If iron particles are sprinkled on a cracked magnet, the particles will be attracted to and cluster not only at the poles at the ends of the magnet, but also at the poles at the edges of the crack. This cluster of particles is much easier to see than the actual crack and this is the basis for magnetic particle inspection.

The first step in a magnetic particle testing is to magnetize the component that is to be inspected. If any defects on or near the surface are present, the defects will create a leakage field. After the component has been magnetized, iron particles, either in a dry or wet suspended form, are applied to the surface of the magnetized part. The particles will be attracted and cluster at the flux leakage fields, thus forming a visible indication that the inspector can detect.




## Advantages and Disadvantages

The primary advantages and disadvantages when compared to other NDT methods are:

*Advantages*

- High sensitivity (*small discontinuities can be detected*).
- Indications are produced directly on the surface of the part and constitute a visual representation of the flaw.
- Minimal surface preparation (*no need for paint removal*)
- Portable (*small portable equipment & materials available in spray cans*)
- Low cost (*materials and associated equipment are relatively inexpensive*)

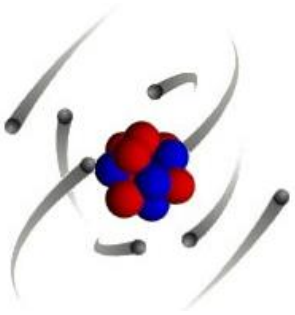
*Disadvantages*

- Only surface and near surface defects can be detected.
- Only applicable to ferromagnetic materials.
- Relatively small area can be inspected at a time.
- Only materials with a relatively nonporous surface can be inspected.
- The inspector must have direct access to the surface being inspected.

## Magnetism

The concept of magnetism centers around the magnetic field and what is known as a dipole. The term "*magnetic field*" simply describes a volume of space where there is a change in energy within that volume. The location where a magnetic field exits or enters a material is called a magnetic pole. Magnetic poles have never been detected in isolation but always occur in pairs, hence the name dipole. Therefore, a dipole is an object that has a magnetic pole on one end and a second, equal but opposite, magnetic pole on the other. A bar magnet is a dipole with a north pole at one end and south pole at the other.

The source of magnetism lies in the basic building block of all matter, the atom. Atoms are composed of protons, neutrons and electrons. The protons and neutrons are located in the atom's nucleus and the electrons are in constant motion around the nucleus. Electrons carry a negative electrical charge and produce a magnetic field as they move through space. A magnetic field is produced whenever an electrical charge is in motion. The strength of this field is called the magnetic moment.

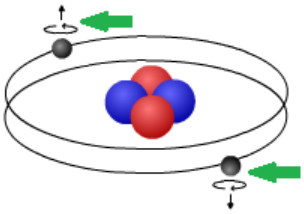


When an electric current flows through a conductor, the movement of electrons through the conductor causes a magnetic field to form around the conductor. The magnetic field can be detected using a compass. Since all matter is comprised of atoms, all materials are affected in some way by a magnetic field; however, materials do not react the same way to the magnetic field.

## Reaction of Materials to Magnetic Field

When a material is placed within a magnetic field, the magnetic forces of the material's electrons will be affected. This effect is known as Faraday's Law of Magnetic Induction. However, materials can react quite differently to the presence of an external magnetic field. The magnetic moments associated with atoms have three origins: the electron motion, the change in motion caused by an external magnetic field, and the spin of the electrons.

In most atoms, electrons occur in pairs where these pairs spin in opposite directions. The opposite spin directions of electron pairs cause their magnetic fields to cancel each other. Therefore, no net magnetic field exists. Alternately, materials with some unpaired



electrons will have a net magnetic field and will react more to an external field.

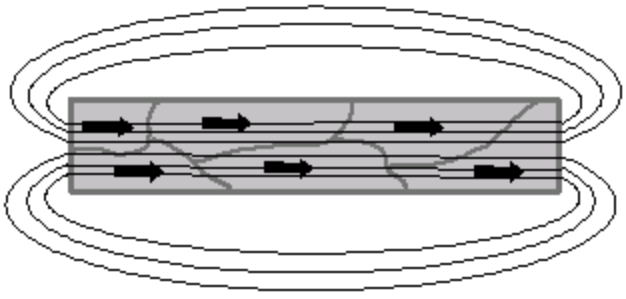
According to their interaction with a magnetic field, materials can be classified as:

***Diamagnetic materials*** which have a weak, negative susceptibility to magnetic fields. Diamagnetic materials are slightly repelled by a magnetic field and the material does not retain the magnetic properties when the external field is removed. In diamagnetic materials all the electrons are paired so there is no permanent net magnetic moment per atom. Most elements in the periodic table, including copper, silver, and gold, are diamagnetic.

***Paramagnetic materials*** which have a small, positive susceptibility to magnetic fields. These materials are slightly attracted by a magnetic field and the material does not retain the magnetic properties when the external field is removed. Paramagnetic materials have some unpaired electrons. Examples of paramagnetic materials include magnesium, molybdenum, and lithium.

***Ferromagnetic materials*** have a large, positive susceptibility to an external magnetic field. They exhibit a strong attraction to magnetic fields and are able to retain their magnetic properties after the external field has been removed. Ferromagnetic materials have some unpaired electrons so their atoms have a net magnetic moment. They get their strong magnetic properties due to the presence of magnetic domains. In these domains, large numbers of atom's moments are aligned parallel so that the magnetic force within the domain is strong (*this happens during the solidification of the material where the atom moments are aligned within each crystal "i.e., grain" causing a strong magnetic force in one direction*). When a ferromagnetic material is in the unmagnetized state, the domains are nearly randomly organized (*since the crystals are in arbitrary directions*) and the net magnetic field for the part as a whole is zero. When a magnetizing force is applied, the domains become aligned to produce a strong magnetic field within the part. Iron, nickel, and cobalt are examples of ferromagnetic materials. Components made of these materials are commonly inspected using the magnetic particle method.

Unmagnetized Material

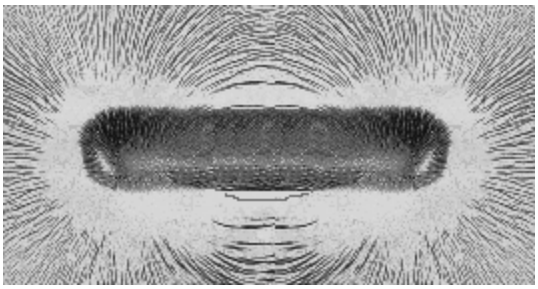


Magnetized Material

## Magnetic Field Characteristics

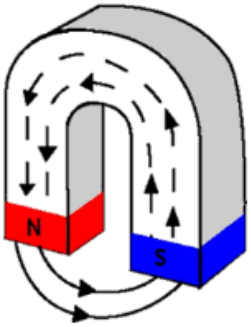
### *Magnetic Field In and Around a Bar Magnet*

The magnetic field surrounding a bar magnet can be seen in the magnetograph below. A magnetograph can be created by placing a piece of paper over a magnet and sprinkling the paper with iron filings. The particles align themselves with the lines of magnetic force produced by the magnet. It can be seen in the magnetograph that there are poles all along the length of the magnet but that the poles are concentrated at the ends of the magnet (*the north and south poles*).



### *Magnetic Fields in and around Horseshoe and Ring Magnets*

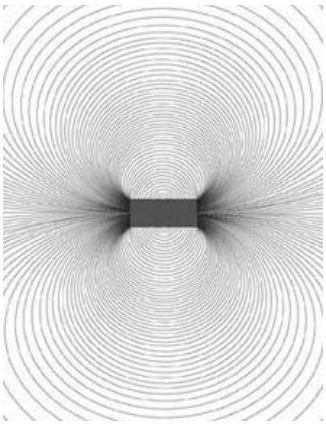
Magnets come in a variety of shapes and one of the more common is the horseshoe (U) magnet. The horseshoe magnet has north and south poles just like a bar magnet but the magnet is curved so the poles lie in the same plane. The magnetic lines of force flow from pole to pole just like in the bar magnet. However, since the poles are located closer together and a more direct path exists for the lines of flux to travel between the poles, the magnetic field is concentrated between the poles.




### *General Properties of Magnetic Lines of Force*

Magnetic lines of force have a number of important properties, which include:

- They seek the path of least resistance between opposite magnetic poles (*in a single bar magnet shown, they attempt to form closed loops from pole to pole*).
- They never cross one another.
- They all have the same strength.
- Their density decreases with increasing distance from the poles.
- Their density decreases (*they spread out*) when they move from an area of higher permeability to an area of lower permeability.



- They are considered to have direction as if flowing, though no actual movement occurs.
- They flow from the south pole to the north pole within a material and north pole to south pole in air.

## Electromagnetic Fields

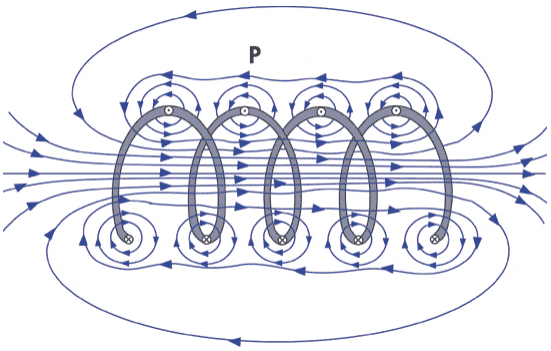
Magnets are not the only source of magnetic fields. The flow of electric current through a conductor generates a magnetic field. When electric current flows in a long straight wire, a circular magnetic field is generated around the wire and the intensity of this magnetic field is directly proportional to the amount of current carried by the wire. The strength of the field is strongest next to the wire and diminishes with distance. In most conductors, the magnetic field exists only as long as the current is flowing. However, in ferromagnetic materials the electric current will cause some or all of the magnetic domains to align and a residual magnetic field will remain.

Also, the direction of the magnetic field is dependent on the direction of the electrical current in the wire. The direction of the magnetic field around a conductor can be determined using a simple rule called the "*right-hand clasp rule*". If a person grasps a conductor in one's right hand with the thumb pointing in the direction of the current, the fingers will circle the conductor in the direction of the magnetic field.

> ***Note:*** *remember that current flows from the positive terminal to the negative terminal (electrons flow in the opposite direction).*

## Magnetic Field Produced by a Coil

When a current carrying wire is formed into several loops to form a coil, the magnetic field circling each loop combines with the fields from the other loops to produce a concentrated field through the center of the coil (*the field flows along the longitudinal axis and circles back around the outside of the coil*).

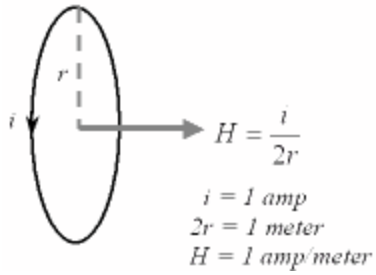


When the coil loops are tightly wound, a uniform magnetic field is developed throughout the length of the coil. The strength of the magnetic field increases not only with increasing current but also with each loop that is added to the coil. A long, straight coil of wire is called a *solenoid* and it can be used to generate a nearly uniform magnetic field similar to that of a bar magnet. The concentrated magnetic field inside a coil is very useful in magnetizing ferromagnetic materials for inspection using the magnetic particle testing method.

## Quantifying Magnetic Properties

The various characteristics of magnetism can be measured and expressed quantitatively. Different systems of units can be used for quantifying magnetic properties. SI units will be used in this material. The advantage of using SI units is that they are traceable back to an agreed set of four base units; meter, kilogram, second, and Ampere.

- The unit for magnetic *field strength* **H** is *ampere/meter* (*A/m*). A magnetic field strength of *1 A/m* is produced at the center of a single circular conductor with a *1 meter* diameter carrying a steady current of *1 ampere*.




- The number of magnetic lines of force cutting through a plane of a given area at a right angle is known as the magnetic *flux density*, **B**. The flux density or magnetic induction has the *Tesla* as its unit. One *Tesla* is equal to *1 Newton/(A/m)*. From these units, it can be seen that the flux density is a measure of the force applied to a particle by the magnetic field.

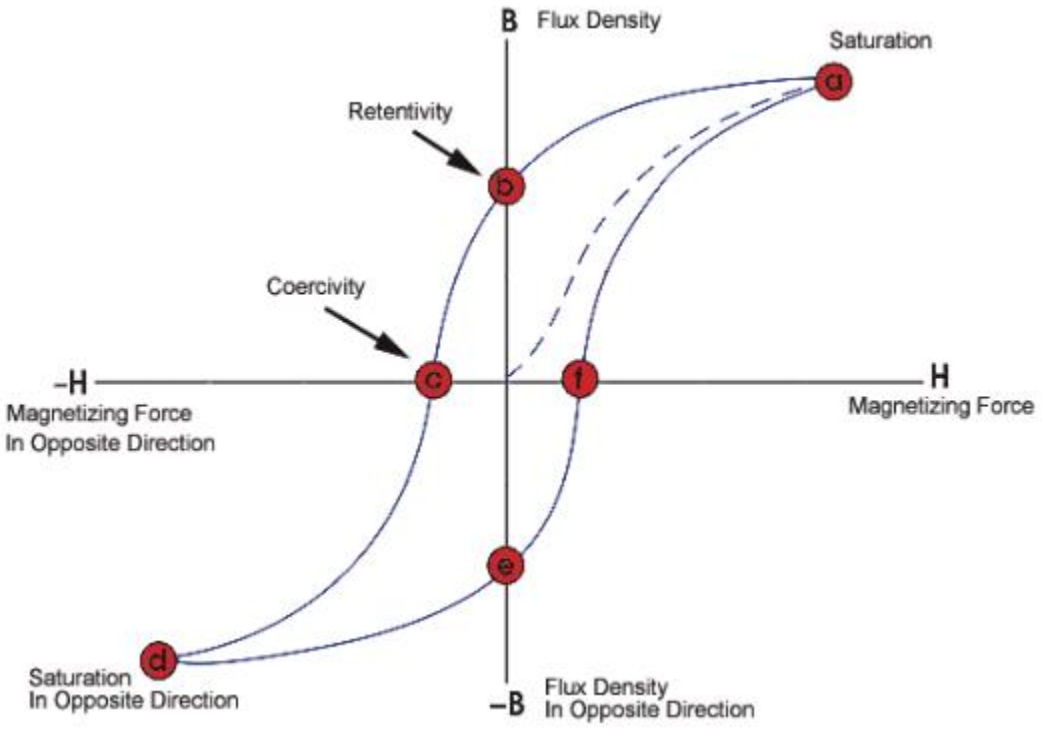
- The total number of lines of magnetic force in a material is called magnetic *flux*, **ϕ**. The strength of the flux is determined by the number of magnetic domains that are aligned within a material. The *total flux* is simply the flux density applied over an area. Flux carries the unit of a *weber*, which is simply a *Tesla-meter*$^2$.

- The *magnetization* **M** is a measure of the extent to which an object is magnetized. It is a measure of the magnetic dipole moment per unit volume of the object. Magnetization carries the same units as a magnetic field *A/m*.

| Quantity | | SI Units (Sommerfeld) | SI Units (Kennelly) | CGS Units (Gaussian) |
|---|---|---|---|---|
| **Field (*Magnetization Force*)** | **H** | A/m | A/m | oersteds |
| **Flux Density (*Magnetic Induction*)** | **B** | Tesla | Tesla | gauss |
| **Flux** | **ϕ** | Weber | Weber | maxwell |
| **Magnetization** | **M** | A/m | - | erg/Oe-cm$^3$ |

## The Hysteresis Loop and Magnetic Properties

A great deal of information can be learned about the magnetic properties of a material by studying its hysteresis loop. A hysteresis loop shows the relationship between the induced magnetic flux density (**B**) and the magnetizing force (**H**). It is often referred to as the *B-H* loop. An example hysteresis loop is shown below.




The loop is generated by measuring the magnetic flux of a ferromagnetic material while the magnetizing force is changed. A ferromagnetic material that has never been previously magnetized or has been thoroughly demagnetized will follow the dashed line as **H** is increased. As the line demonstrates, the greater the amount of current applied (***H+***), the stronger the magnetic field in the component (***B+***). At point "***a***"

almost all of the magnetic domains are aligned and an additional increase in the magnetizing force will produce very little increase in magnetic flux. The material has reached the point of magnetic saturation. When **H** is reduced to zero, the curve will move from point "***a***" to point "***b***". At this point, it can be seen that some magnetic flux remains in the material even though the magnetizing force is zero. This is referred to as the point of retentivity on the graph and indicates the level of residual magnetism in the material (*Some of the magnetic domains remain aligned but some have lost their alignment*). As the magnetizing force is reversed, the curve moves to point "***c***", where the flux has been reduced to zero. This is called the point of coercivity on the curve (*the reversed magnetizing force has flipped enough of the domains so that the net flux within the material is zero*). The force required to remove the residual magnetism from the material is called the coercive force or coercivity of the material.

As the magnetizing force is increased in the negative direction, the material will again become magnetically saturated but in the opposite direction, point "***d***". Reducing **H** to zero brings the curve to point "***e***". It will have a level of residual magnetism equal to that achieved in the other direction. Increasing **H** back in the positive direction will return **B** to zero. Notice that the curve did not return to the origin of the graph because some force is required to remove the residual magnetism. The curve will take a different path from point "***f***" back to the saturation point where it with complete the loop.

From the hysteresis loop, a number of primary magnetic properties of a material can be determined:

1. ***Retentivity*** - A measure of the residual flux density corresponding to the saturation induction of a magnetic material. In other words, it is a material's ability to retain a certain amount of residual magnetic field when the magnetizing force is removed after achieving saturation (The value of **B** at point ***b*** on the hysteresis curve).
2. ***Residual Magnetism or Residual Flux*** - The magnetic flux density that remains in a material when the magnetizing force is zero. Note that residual magnetism and retentivity are the same when the material has been magnetized to the saturation point. However, the level of residual magnetism may be lower than the retentivity value when the magnetizing force did not reach the saturation level.
3. ***Coercive Force*** - The amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero (The value of **H** at point ***c*** on the hysteresis curve).
4. ***Permeability, μ*** - A property of a material that describes the ease with which a magnetic flux is established in the material.

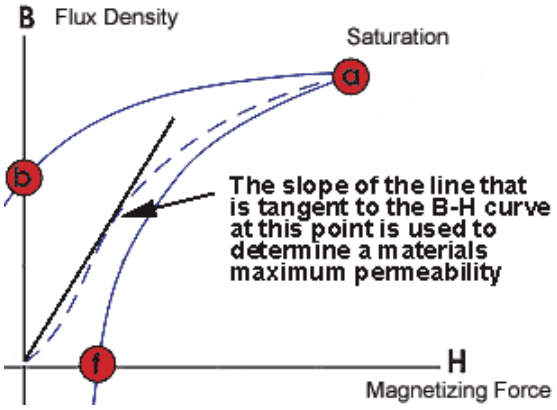
5. ***Reluctance*** - Is the opposition that a ferromagnetic material shows to the establishment of a magnetic field. Reluctance is analogous to the resistance in an electrical circuit.

## Permeability

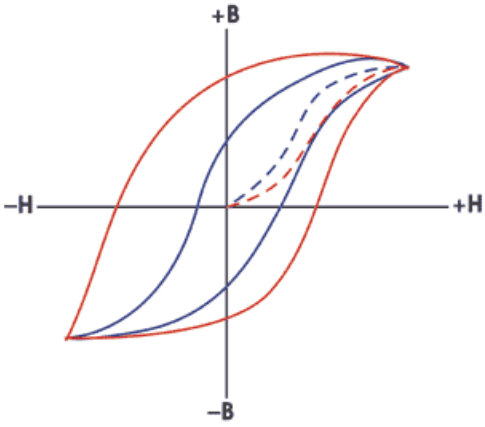
As previously mentioned, permeability ($\mu$) is a material property that describes the ease with which a magnetic flux is established in a component. It is the ratio of the flux density (B) created within a material to the magnetizing field (H) and it is represented by the following equation:

$$\mu = B/H$$

This equation describes the slope of the curve at any point on the hysteresis loop. The permeability value given in letrature for materials is usually the maximum permeability or the maximum relative permeability. The maximum permeability is the point where the slope of the B/H curve for the unmagnetized material is the greatest. This point is often taken as the point where a straight line from the origin is tangent to the B/H curve.




The shape of the hysteresis loop tells a great deal about the material being magnetized. The hysteresis curves of two different materials are shown in the graph.

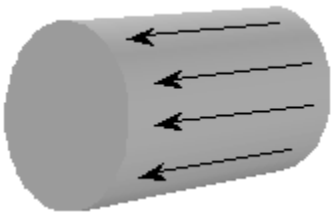



- Relative to other materials, a material with a wider hysteresis loop has:
  - Lower Permeability
  - Higher Retentivity
  - Higher Coercivity
  - Higher Reluctance
  - Higher Residual Magnetism
- Relative to other materials, a material with a narrower hysteresis loop has:
  - Higher Permeability
  - Lower Retentivity
  - Lower Coercivity
  - Lower Reluctance
  - Lower Residual Magnetism

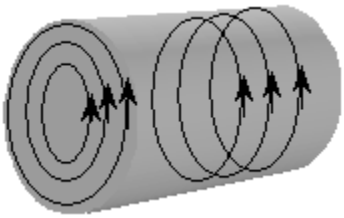
In magnetic particle testing, the level of residual magnetism is important. Residual magnetic fields are affected by the permeability, which can be related to the carbon content and alloying of the material. A component with high carbon content will have low permeability and will retain more magnetic flux than a material with low carbon content.

## Magnetic Field Orientation and Flaw Detectability

To properly inspect a component for cracks or other defects, it is important to understand that the orientation of the crack relative to the magnetic lines of force determinies if the crack can or cannot be detected. There are two general types of magnetic fields that can be established within a component.

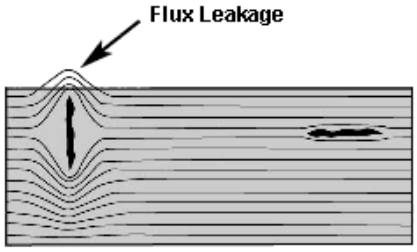


- *A longitudinal magnetic field* has magnetic lines of force that run parallel to the long axis of the part. Longitudinal magnetization of a component can be accomplished using the longitudinal field set up by a coil or solenoid. It can also be accomplished using permanent magnets or electromagnets.

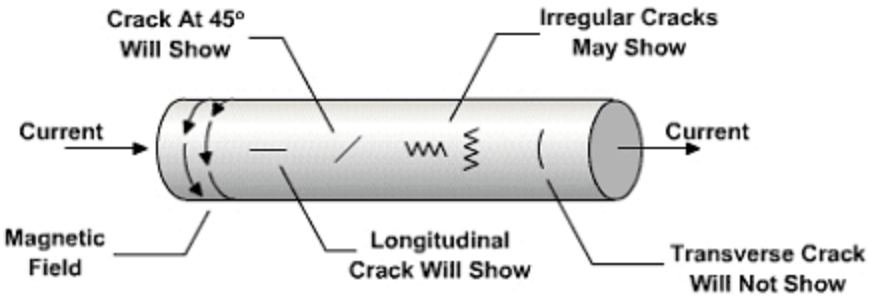


- *A circular magnetic field* has magnetic lines of force that run circumferentially around the perimeter of a part. A circular magnetic field is induced in an article by either passing current through the component or by passing current through a conductor surrounded by the component.

The type of magnetic field established is determined by the method used to magnetize the specimen. Being able to magnetize the part in two directions is important because the best detection of defects occurs when the lines of magnetic force are established at right angles to the longest dimension of the defect. This orientation creates the largest disruption of the magnetic field within the part and the greatest flux leakage at the surface of the part. If the magnetic field is parallel to the defect, the field will see little disruption and no flux leakage field will be produced.



An orientation of 45 to 90 degrees between the magnetic field and the defect is necessary to form an indication. Since defects may occur in various and unknown directions, each part is normally magnetized in two directions at right angles to each other. If the component shown is considered, it is known that passing current through the part from end to end will establish a circular magnetic field that will be 90 degrees to the direction of the current. Therefore, defects that have a significant dimension in the direction of the current (*longitudinal defects*) should be detectable, while transverse-type defects will not be detectable with circular magnetization.




## Magnetization of Ferromagnetic Materials

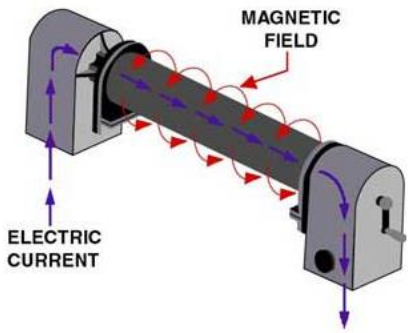
There are a variety of methods that can be used to establish a magnetic field in a component for evaluation using magnetic particle inspection. It is common to classify the magnetizing methods as either direct or indirect.

*Magnetization Using Direct Induction (Direct Magnetization)*

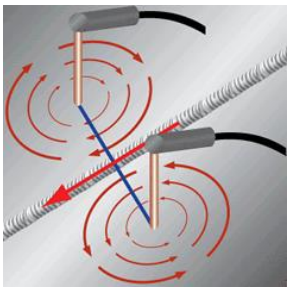
With direct magnetization, current is passed directly through the component. The flow of current causes a circular magnetic field to form in and around the conductor. When using the direct magnetization method, care must be taken to ensure that good electrical contact is established and maintained between the test equipment and the test component to avoid damage of the the component (*due to arcing or overheating at high resistance ponts*).

There are several ways that direct magnetization is commonly accomplished.

- One way involves *clamping the component between two electrical contacts* in a special piece of equipment. Current is passed through the component and a circular magnetic field is established in and around the component. When the magnetizing current is stopped, a residual magnetic field will remain within the component. The strength of the induced magnetic field is proportional to the amount of current passed through the component.



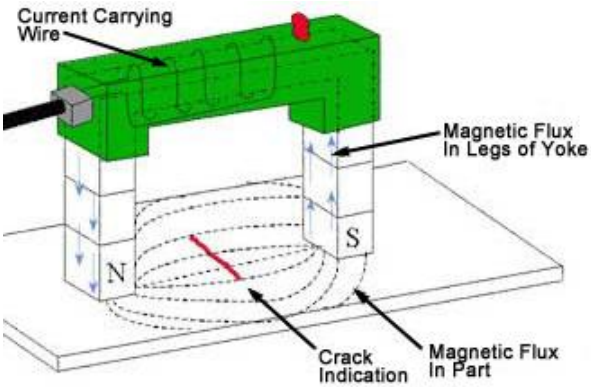
- A second technique involves using *clamps or prods*, which are attached or placed in contact with the component. Electrical current flows through the component from contact to contact. The current sets up a circular magnetic field around the path of the current.



*Magnetization Using Indirect Induction (Indirect Magnetization)*

Indirect magnetization is accomplished by using a strong external magnetic field to establish a magnetic field within the component. As with direct magnetization, there are several ways that indirect magnetization can be accomplished.

- The use of *permanent magnets* is a low cost method of establishing a magnetic field. However, their use is limited due to lack of control of the field strength and the difficulty of placing and removing strong permanent magnets from the component.

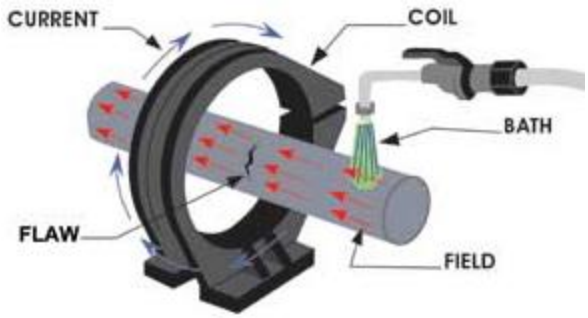



- *Electromagnets* in the form of an adjustable horseshoe magnet (*called a yoke*) eliminate the problems associated with permanent magnets and are used extensively in industry. Electromagnets only exhibit a magnetic flux when electric current is flowing around the soft iron core. When the magnet is placed on the component, a magnetic field is established between the north and south poles of the magnet.


- Another way of indirectly inducting a magnetic field in a material is by using the magnetic field of a current carrying conductor. A circular magnetic field can be established in cylindrical components by using a *central conductor*. Typically, one or more cylindrical components are hung from a solid copper bar running through the inside diameter. Current is passed through the copper bar and the resulting circular magnetic field establishes a magnetic field within the test components.

- The use of *coils and solenoids* is a third method of indirect magnetization. When the length of a component is several times larger than its diameter, a longitudinal

magnetic field can be established in the component. The component is placed longitudinally in the concentrated magnetic field that fills the center of a coil or solenoid. This magnetization technique is often referred to as a "*coil shot*".




## Types of Magnetizing Current

As mentioned previously, electric current is often used to establish the magnetic field in components during magnetic particle inspection. Alternating current (AC) and direct current (DC) are the two basic types of current commonly used. The type of current used can have an effect on the inspection results, so the types of currents commonly used are briefly discussed here.

### *Direct Current*

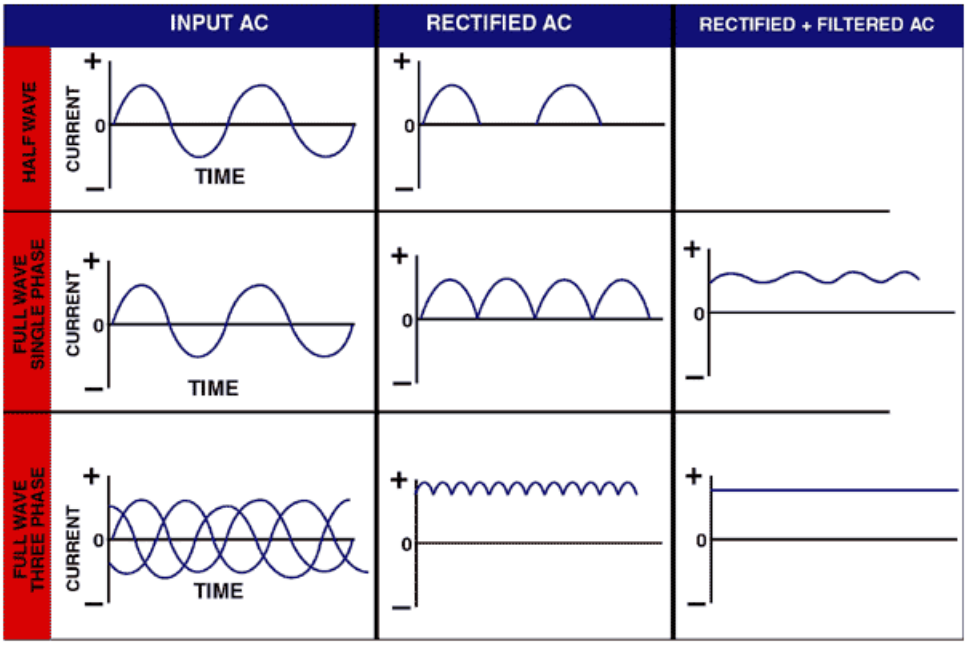
Direct current (DC) flows continuously in one direction at a constant voltage. A battery is the most common source of direct current. The current is said to flow from the positive to the negative terminal, though electrons flow in the opposite direction. DC is very desirable when inspecting for subsurface defects because DC generates a magnetic field that penetrates deeper into the material. In ferromagnetic materials, the magnetic field produced by DC generally penetrates the entire cross-section of the component.

### *Alternating Current*

Alternating current (AC) reverses its direction at a rate of 50 or 60 cycles per second. Since AC is readily available in most facilities, it is convenient to make use of it for magnetic particle inspection. However, when AC is used to induce a magnetic field in ferromagnetic materials, the magnetic field will be limited to a thin layer at the surface of the component. This phenomenon is known as the "*skin effect*" and it occurs because the changing magnetic field generates eddy currents in the test object. The eddy currents produce a magnetic field that opposes the primary field, thus reducing the net magnetic flux below the surface. Therefore, it is recommended that AC be used only when the inspection is limited to surface defects.

### *Rectified Alternating Current*

Clearly, the skin effect limits the use of AC since many inspection applications call for the detection of subsurface defects. Luckily, AC can be converted to current that is very much like DC through the process of rectification. With the use of rectifiers, the reversing AC can be converted to a one directional current. The three commonly used types of rectified current are described below.




*Half Wave Rectified Alternating Current (HWAC)*

When single phase alternating current is passed through a rectifier, current is allowed to flow in only one direction. The reverse half of each cycle is blocked out so that a one directional, pulsating current is produced. The current rises from zero to a maximum and then returns to zero. No current flows during the time when the reverse cycle is blocked out. The HWAC repeats at same rate as the unrectified current (50 or 60 Hz). Since half of the current is blocked out, the amperage is half of the unaltered AC. This type of current is often referred to as *half wave DC or pulsating DC*. The pulsation of the HWAC helps in forming magnetic particle indications by vibrating the particles and giving them added mobility where that is especially important when using dry particles. HWAC is most often used to power electromagnetic yokes.

*Full Wave Rectified Alternating Current (FWAC)* (***Single Phase***)

Full wave rectification inverts the negative current to positive current rather than blocking it out. This produces a pulsating DC with no interval between the pulses. Filtering is usually performed to soften the sharp polarity switching in the rectified

current. While particle mobility is not as good as half-wave AC due to the reduction in pulsation, the depth of the subsurface magnetic field is improved.

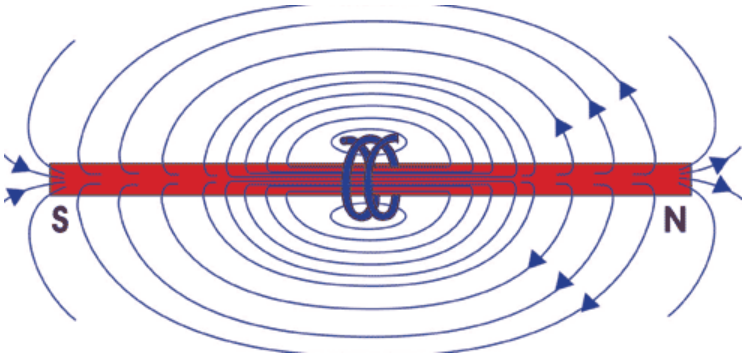
*Three Phase Full Wave Rectified Alternating Current*

Three phase current is often used to power industrial equipment because it has more favorable power transmission and line loading characteristics. This type of electrical current is also highly desirable for magnetic particle testing because when it is rectified and filtered, the resulting current very closely resembles direct current. Stationary magnetic particle equipment wired with three phase AC will usually have the ability to magnetize with AC or DC (*three phase full wave rectified*), providing the inspector with the advantages of each current form.

## Magnetic Fields Distribution and Intensity

### *Longitudinal Fields*

When a long component is magnetized using a solenoid having a shorter length, only the material within the solenoid and about the same length on each side of the solenoid will be strongly magnetized. This occurs because the magnetizing force diminishes with increasing distance from the solenoid. Therefore, a long component must be magnetized and inspected at several locations along its length for complete inspection coverage.




### *Circular Fields*

When a circular magnetic field forms in and around a conductor due to the passage of electric current through it, the following can be said about the distribution and intensity of the magnetic field:

- The field strength varies from zero at the center of the component to a maximum at the surface.
- The field strength at the surface of the conductor decreases as the radius of the conductor increases (*when the current strength is held constant*).

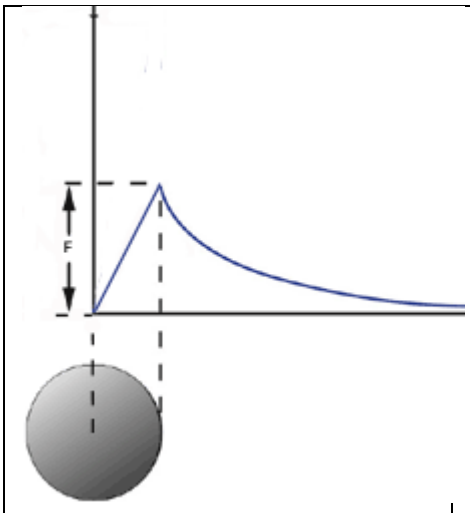
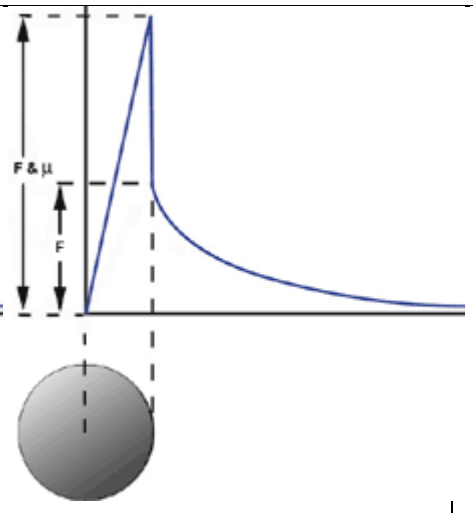
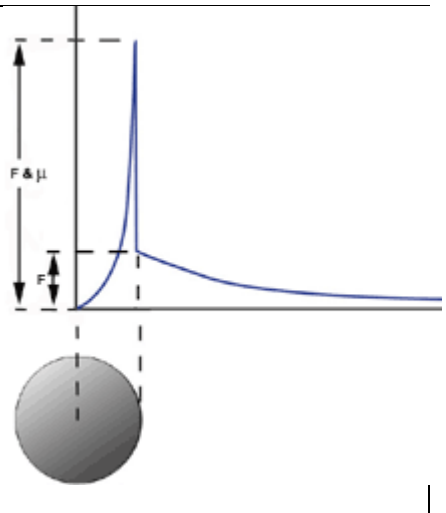
- The field strength inside the conductor is dependent on the current strength, magnetic permeability of the material, and, if ferromagnetic, the location on the B-H curve.
- The field strength outside the conductor is directly proportional to the current strength and it decreases with distance from the conductor.

The images below show the magnetic field strength graphed versus distance from the center of the conductor when current passes through a solid circular conductor.

- In a nonmagnetic conductor carrying DC, the internal field strength rises from zero at the center to a maximum value at the surface of the conductor.

- In a magnetic conductor carrying DC, the field strength within the conductor is much greater than it is in the nonmagnetic conductor. This is due to the permeability of the magnetic material. The external field is exactly the same for the two materials provided the current level and conductor radius are the same.

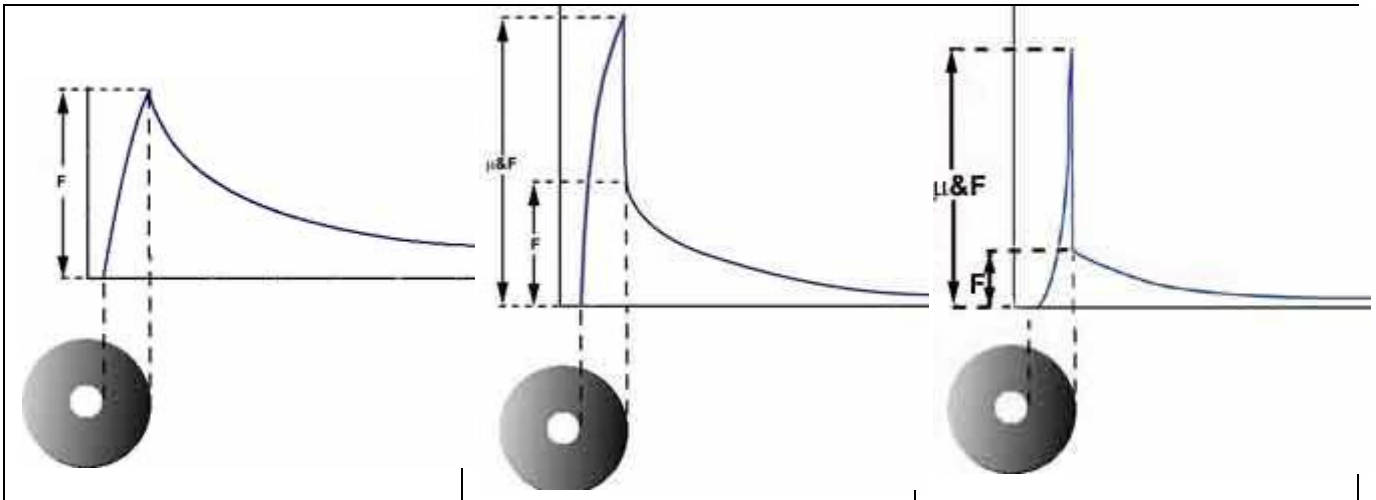
- When the magnetic conductor is carrying AC, the internal magnetic field will be concentrated in a thin layer near the surface of the conductor (*skin effect*). The external field decreases with increasing distance from the surface same as with DC.

|  |  |  |
|---|---|---|
| The magnetic field distribution in and around a solid conductor of a nonmagnetic material carrying direct current. | The magnetic field distribution in and around a solid conductor of a magnetic material carrying direct current. | The magnetic field distribution in and around a solid conductor of a magnetic material carrying alternating current. |

In a hollow circular conductor there is no magnetic field in the void area. The magnetic field is zero at the inner surface and rises until it reaches a maximum at the outer surface.

- Same as with a solid conductor, when DC current is passed through a magnetic conductor, the field strength within the conductor is much greater than in nonmagnetic conductor due to the permeability of the magnetic material. The external field strength decreases with distance from the surface of the conductor. The external field is exactly the same for the two materials provided the current level and conductor radius are the same.

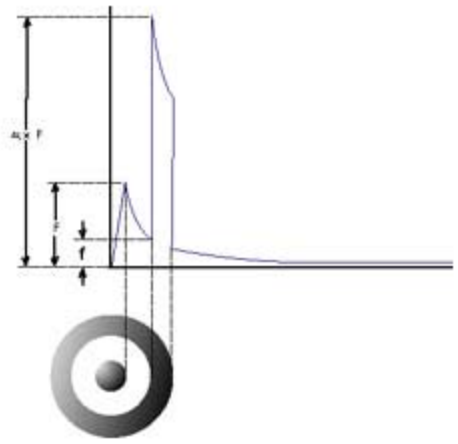
- When AC current is passed through a hollow circular magnetic conductor, the skin effect concentrates the magnetic field at the outside diameter of the component.




| | | |
|---|---|---|
| The magnetic field distribution in and around a hollow conductor of a nonmagnetic material carrying direct current. | The magnetic field distribution in and around a hollow conductor of a magnetic material carrying direct current. | The magnetic field distribution in and around a hollow conductor of a magnetic material carrying alternating current. |

As can be seen from these three field distribution images, the field strength at the inside surface of hollow conductor is very low when a circular magnetic field is established by direct magnetization. Therefore, the direct method of magnetization is not recommended when inspecting the inside diameter wall of a hollow component for shallow defects (*if the defect has significant depth, it may be detectable using DC since the field strength increases rapidly as one moves from the inner towards the outer surface*).

- A much <u>better method</u> of magnetizing hollow components for inspection of the ID and OD surfaces is with the use of a <u>central conductor</u>. As can be seen in the field distribution image, when current is passed through a nonmagnetic central conductor (copper bar), the magnetic field produced on the inside diameter surface of a magnetic tube is much greater and the field is still strong enough for defect detection on the OD surface.



The magnetic field distribution in and around a nonmagnetic central conductor carrying DC inside a hollow conductor of a magnetic material.

## Demagnetization

After conducting a magnetic particle inspection, it is usually necessary to demagnetize the component. Remanent magnetic fields can:

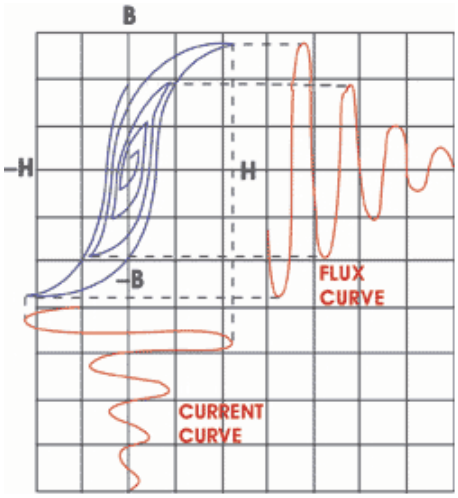
- affect machining by causing cuttings to cling to a component.
- interfere with electronic equipment such as a compass.
- create a condition known as "*arc blow*" in the welding process. Arc blow may cause the weld arc to wonder or filler metal to be repelled from the weld.
- cause abrasive particles to cling to bearing or faying surfaces and increase wear.

Removal of a field may be accomplished in several ways. The most effective way to demagnetize a material is by <u>heating the material above its curie temperature</u> (*for instance, the curie temperature for a low carbon steel is 770°C*). When steel is heated above its curie temperature then it is cooled back down, the the orientation of the magnetic domains of the individual grains will become randomized again and thus the component will contain no residual magnetic field. The material should also be <u>placed with its long axis in an east-west orientation</u> to avoid any influence of the Earth's magnetic field.

However, it is often inconvenient to heat a material above its curie temperature to demagnetize it, so another method that returns the material to a nearly unmagnetized state is commonly used.

Subjecting the component to a <u>reversing and decreasing magnetic field</u> will return the dipoles to a nearly random orientation throughout the material. This can be accomplished by <u>pulling a component out and away from a coil</u> with AC passing

through it. With AC Yokes, demagnetization of local areas may be accomplished by placing the yoke contacts on the surface, moving them in circular patterns around the area, and slowly withdrawing the yoke while the current is applied. Also, many stationary magnetic particle inspection units come with a demagnetization feature that slowly reduces the AC in a coil in which the component is placed.




A field meter is often used to verify that the residual flux has been removed from a component. Industry standards usually require that the magnetic flux be reduced to less than 3 Gauss (*$3x10^{-4}$ Tesla*) after completing a magnetic particle inspection.

## Measuring Magnetic Fields

When performing a magnetic particle inspection, it is very important to be able to determine the direction and intensity of the magnetic field. The field intensity must be high enough to cause an indication to form, but not too high to cause nonrelevant indications to mask relevant indications. Also, after magnetic inspection it is often needed to measure the level of residual magnetezm.

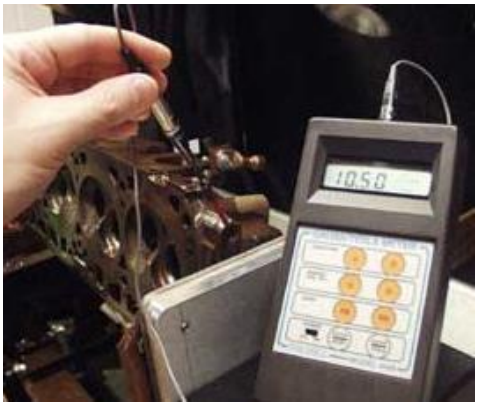
Since it is impractical to measure the actual field strength within the material, all the devices measure the magnetic field that is outside of the material. The two devices commonly used for quantitative measurement of magnetic fields n magnetic particle inspection are the field indicator and the Hall-effect meter, which is also called a gauss meter.

### *Field Indicators*

Field indicators are small mechanical devices that utilize a soft iron vane that is deflected by a magnetic field. The vane is attached to a needle that rotates and moves the pointer on the scale. Field indicators can be adjusted and calibrated so that quantitative information can be obtained. However, the measurement range of field indicators is usually small due to the mechanics of the device (*the one shown in the image has a range from plus 20 to minus 20 Gauss*). This limited range makes them best suited for measuring the residual magnetic field after demagnetization.

### *Hall-Effect (Gauss/Tesla) Meter*

A Hall-effect meter is an electronic device that provides a digital readout of the magnetic field strength in Gauss or Tesla units. The meter uses a very small conductor or semiconductor element at the tip of the probe. Electric current is passed through the conductor. In a magnetic field, a force is exerted on the moving electrons which tends to push them to one side of the conductor. A buildup of charge at the sides of the conductors will balance this magnetic influence, producing a measurable voltage between the two sides of the conductor. The probe is placed in the magnetic field such that the magnetic lines of force intersect the major dimensions of the sensing element at a right angle.



## Magnetization Equipment for Magnetic Particle Testing

To properly inspect a part for cracks or other defects, it is important to become familiar with the different types of magnetic fields and the equipment used to generate them. As discussed previously, one of the primary requirements for detecting a defect in a ferromagnetic material is that the magnetic field induced in the part must intercept the defect at a 45 to 90 degree angle. Flaws that are normal (90 degrees) to the magnetic field will produce the strongest indications because they disrupt more of the magnet flux. Therefore, for proper inspection of a component, it is important to be able to establish a magnetic field in at least two directions.

A variety of equipment exists to establish the magnetic field for magnetic particle testing. One way to classify equipment is based on its portability. Some equipment is designed to be portable so that inspections can be made in the field and some is designed to be stationary for ease of inspection in the laboratory or manufacturing facility.

### *Portable Equipment*

*Permanent Magnets*

Permanent magnets can be used for magnetic particle inspection as the source of magnetism (*bar magnets or horseshoe magnets*). The use of industrial magnets is not popular because they are very strong (*they require significant strength to remove them*

*from the surface, about 250 N for some magnets*) and thus they are difficult and sometimes dangerous to handle. However, permanent magnets are sometimes used by divers for inspection in underwater environments or other areas, such as explosive environments, where electromagnets cannot be used. Permanent magnets can also be made small enough to fit into tight areas where electromagnets might not fit.

*Electromagnetic Yokes*

An electromagnetic yoke is a very common piece of equipment that is used to establish a magnetic field. A switch is included in the electrical circuit so that the current and, therefore, the magnetic field can be turned on and off. They can be powered with AC from a wall socket or by DC from a battery pack. This type of magnet generates a very strong magnetic field in a local area where the poles of the magnet touch the part being inspected. Some yokes can lift weights in excess of 40 pounds.

*Prods*

Prods are handheld electrodes that are pressed against the surface of the component being inspected to make contact for passing electrical current (*AC or DC*) through the metal. Prods are typically made from copper and have an insulated handle to help protect the operator. One of the prods has a trigger switch so that the current can be quickly and easily turned on and off. Sometimes the two prods are connected by any insulator, as shown in the image, to facilitate one hand operation. This is referred to as a dual prod and is commonly used for weld inspections.

However, caution is required when using prods because electrical arcing can occur and cause damage to the component if proper contact is not maintained between the prods and the component surface. For this reason, the use of prods is not allowed when inspecting aerospace and other critical components. To help prevent arcing, the

prod tips should be inspected frequently to ensure that they are not oxidized, covered with scale or other contaminant, or damaged.

*Portable Coils and Conductive Cables*

Coils and conductive cables are used to establish a longitudinal magnetic field within a component. When a preformed coil is used, the component is placed against the inside surface on the coil. Coils typically have three or five turns of a copper cable within the molded frame. A foot switch is often used to energize the coil.

Also, flexible conductive cables can be wrapped around a component to form a coil. The number of wraps is determined by the magnetizing force needed and of course, the length of the cable. Normally, the wraps are kept as close together as possible. When using a coil or cable wrapped into a coil, amperage is usually expressed in ampere-turns. Ampere-turns is the amperage shown on the amp meter times the number of turns in the coil.

*Portable Power Supplies*

Portable power supplies are used to provide the necessary electricity to the prods, coils or cables. Power supplies are commercially available in a variety of sizes. Small power supplies generally provide up to 1,500A of half-wave DC or AC. They are small and light enough to be carried and operate on either 120V or 240V electrical service.

When more power is necessary, mobile power supplies can be used. These units come with wheels so that they can be rolled where needed. These units also operate on 120V or 240V electrical service and can provide up to 6,000A of AC or half-wave DC.

### *Stationery Equipment*

Stationary magnetic particle inspection equipment is designed for use in laboratory or production environment. The most common stationary system is the wet horizontal (bench) unit. Wet horizontal units are designed to allow for batch inspections of a variety of components. The units have head and tail stocks (*similar to a lathe*) with electrical contact that the part can be clamped between. A circular magnetic field is produced with direct magnetization.

Most units also have a movable coil that can be moved into place so the indirect magnetization can be used to produce a longitudinal magnetic field. Most coils have five turns and can be obtained in a variety of sizes. The wet magnetic particle solution is collected and held in a tank. A pump and hose system is used to apply the particle solution to the components being inspected. Some of the systems offer a variety of options in electrical current used for magnetizing the component (*AC, half wave DC, or full wave DC*). In some units, a demagnetization feature is built in, which uses the coil and decaying AC.

## Magnetic Field Indicators

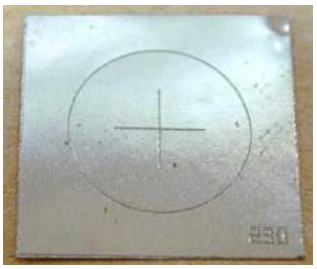
Determining whether a magnetic field is of adequate strength and in the proper direction is critical when performing magnetic particle testing. There is actually no easy-to-apply method that permits an exact measurement of field intensity at a given point within a material. Cutting a small slot or hole into the material and measuring the leakage field that crosses the air gap with a Hall-effect meter is probably the best way to get an estimate of the actual field strength within a part. However, since that is not practical, there are a number of tools and methods that are used to determine the presence and direction of the field surrounding a component.

### *Hall-Effect Meter (Gauss Meter)*

As discussed earlier, a Gauss meter is commonly used to measure the tangential field strength on the surface of the part. By placing the probe next to the surface, the meter

measures the intensity of the field in the air adjacent to the component when a magnetic field is applied. The advantages of this device are: it provides a quantitative measure of the strength of magnetizing force tangential to the surface of a test piece, it can be used for measurement of residual magnetic fields, and it can be used repetitively. The main disadvantage is that such devices must be periodically calibrated.

### *Quantitative Quality Indicator (QQI)*



The Quantitative Quality Indicator (QQI) or *Artificial Flaw Standard* is often the preferred method of assuring proper field direction and adequate field strength (*it is used with the wet method only*). The QQI is a thin strip (*0.05 or 0.1 mm thick*) of AISI 1005 steel with a specific pattern, such as concentric circles or a plus sign, etched on it. The QQI is placed directly on the surface, with the itched side facing the surface, and it is usually fixed to the surface using a tape then the component is then magnetized and particles applied. When the field strength is adequate, the particles will adhere over the engraved pattern and provide information about the field direction.

### *Pie Gage*

The pie gage is a disk of highly permeable material divided into four, six, or eight sections by non-ferromagnetic material (*such as copper*). The divisions serve as artificial defects that radiate out in different directions from the center. The sections are furnace brazed and copper plated. The gage is placed on the test piece copper side up and the test piece is magnetized. After particles are applied and the excess removed, the indications provide the inspector the orientation of the magnetic field. Pie gages are mainly used on flat surfaces such as weldments or steel castings where dry powder is used with a yoke or prods. The pie gage is not recommended for precision parts with complex shapes, for wet-method applications, or for proving field magnitude. The gage should be demagnetized between readings.

### *Slotted Strips*

Slotted strips are pieces of highly permeable ferromagnetic material with slots of different widths. These strips can be used with the wet or dry method. They are placed

on the test object as it is inspected. The indications produced on the strips give the inspector a general idea of the field strength in a particular area.

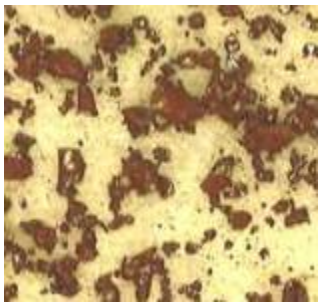
## Magnetic Particles

As mentioned previously, the particles that are used for magnetic particle inspection are a key ingredient as they form the indications that alert the inspector to the presence of defects. Particles start out as tiny milled pieces of iron or iron oxide. A pigment (*somewhat like paint*) is bonded to their surfaces to give the particles color. The metal used for the particles has high magnetic permeability and low retentivity. High magnetic permeability is important because it makes the particles attract easily to small magnetic leakage fields from discontinuities, such as flaws. Low retentivity is important because the particles themselves never become strongly magnetized so they do not stick to each other or the surface of the part. Particles are available in a dry mix or a wet solution.

### *Dry Magnetic Particles*

Dry magnetic particles can typically be purchased in red, black, gray, yellow and several other colors so that a high level of contrast between the particles and the part being inspected can be achieved. The size of the magnetic particles is also very important. Dry magnetic particle products are produced to include a range of particle sizes. The fine particles have a diameter of about 50 µm while the course particles have a diameter of 150 µm (*fine particles are more than 20 times lighter than the coarse particles*). This makes fine particles more sensitive to the leakage fields from very small discontinuities. However, dry testing particles cannot be made exclusively of the fine particles where coarser particles are needed to bridge large discontinuities and to reduce the powder's dusty nature. Additionally, small particles easily adhere to surface contamination, such as remnant dirt or moisture, and get trapped in surface roughness features. It should also be recognized that finer particles will be more easily blown away by the wind; therefore, windy conditions can reduce the sensitivity of an inspection. Also, reclaiming the dry particles is not recommended because the small particles are less likely to be recaptured and the "once used" mix will result in less sensitive inspections.

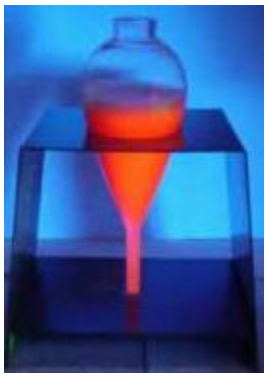
The particle shape is also important. Long, slender particles tend to align themselves along the lines of magnetic force. However, if dry powder consists only of elongated particles, the application process would be less than desirable since long particles lack the ability to flow freely. Therefore, a mix of rounded and elongated particles is used since it results in a dry powder that flows well and maintains good sensitivity. Most dry particle mixes have particles with L/D ratios between one and two.



***Wet Magnetic Particles***

Magnetic particles are also supplied in a wet suspension such as water or oil. The wet magnetic particle testing method is generally more sensitive than the dry because the suspension provides the particles with more mobility and makes it possible for smaller particles to be used (*the particles are typically 10 µm and smaller*) since dust and adherence to surface contamination is reduced or eliminated. The wet method also makes it easy to apply the particles uniformly to a relatively large area.

Wet method magnetic particles products differ from dry powder products in a number of ways. One way is that both visible and fluorescent particles are available. Most non-fluorescent particles are ferromagnetic iron oxides, which are either black or brown in color. Fluorescent particles are coated with pigments that fluoresce when exposed to ultraviolet light. Particles that fluoresce green-yellow are most common to take advantage of the peak color sensitivity of the eye but other fluorescent colors are also available.



The carrier solutions can be water or oil-based. Water-based carriers form quicker indications, are generally less expensive, present little or no fire hazard, give off no petrochemical fumes, and are easier to clean from the part. Water-based solutions are usually formulated with a corrosion inhibitor to offer some corrosion protection. However, oil-based carrier solutions offer superior corrosion and hydrogen embrittlement protection to those materials that are prone to attack by these mechanisms.

Also, both visible and fluorescent wet suspended particles are available in aerosol spray cans for increased portability and ease of application.

## Dry Particle Inspection

In this magnetic particle testing technique, dry particles are dusted onto the surface of the test object as the item is magnetized. Dry particle inspection is well suited for the inspections conducted on rough surfaces. When an electromagnetic yoke is used, the AC current creates a pulsating magnetic field that provides mobility to the powder.

Dry particle inspection is also used to detect shallow subsurface cracks. Dry particles with half wave DC is the best approach when inspecting for lack of root penetration in welds of thin materials.

*Steps for performing dry particles inspection*:

- ***Surface preparation*** - The surface should be relatively clean but this is not as critical as it is with liquid penetrant inspection. The surface must be free of grease, oil or other moisture that could keep particles from moving freely. A thin layer of paint, rust or scale will reduce test sensitivity but can sometimes be left in place with adequate results. Specifications often allow up to 0.076 mm of a nonconductive coating (*such as paint*) or 0.025 mm of a ferromagnetic coating (*such as nickel*) to be left on the surface. Any loose dirt, paint, rust or scale must be removed.

    - Some specifications require the surface to be coated with a thin layer of white paint in order to improve the contrast difference between the background and the particles (*especially when gray color particles are used*).

- ***Applying the magnetizing force*** - Use permanent magnets, an electromagnetic yoke, prods, a coil or other means to establish the necessary magnetic flux.

- ***Applying dry magnetic particles*** - Dust on a light layer of magnetic particles.

- ***Blowing off excess powder*** - With the magnetizing force still applied, remove the excess powder from the surface with a few gentle puffs of dry air. The force of the air needs to be strong enough to remove the excess particles but not strong enough to remove particles held by a magnetic flux leakage field.

- ***Terminating the magnetizing force*** - If the magnetic flux is being generated with an electromagnet or an electromagnetic field, the magnetizing force should be terminated. If permanent magnets are being used, they can be left in place.

- ***Inspection for indications*** - Look for areas where the magnetic particles are clustered.

## Wet Suspension Inspection

Wet suspension magnetic particle inspection, more commonly known as wet magnetic particle inspection, involves applying the particles while they are suspended in a liquid carrier. Wet magnetic particle inspection is most commonly performed using a stationary, wet, horizontal inspection unit but suspensions are also available in spray cans for use with an electromagnetic yoke.

A wet inspection has several advantages over a dry inspection. First, all of the surfaces of the component can be quickly and easily covered with a relatively uniform layer of particles. Second, the liquid carrier provides mobility to the particles for an extended period of time, which allows enough particles to float to small leakage fields to form a visible indication. Therefore, wet inspection is considered best for detecting very small discontinuities on smooth surfaces. On rough surfaces, however, the particles (*which are much smaller in wet suspensions*) can settle in the surface valleys and lose mobility, rendering them less effective than dry powders under these conditions.

*Steps for performing wet particle inspection*:

- ***Surface preparation*** - Just as is required with dry particle inspections, the surface should be relatively clean. The surface must be free of grease, oil and other moisture that could prevent the suspension from wetting the surface and preventing the particles from moving freely. A thin layer of paint, rust or scale will reduce test sensitivity, but can sometimes be left in place with adequate results. Specifications often allow up to 0.076 mm of a nonconductive coating (*such as paint*) or 0.025 mm of a ferromagnetic coating (*such as nickel*) to be left on the surface. Any loose dirt, paint, rust or scale must be removed.

    - Some specifications require the surface to be coated with a thin layer of white paint when inspecting using visible particles in order to improve the contrast

difference between the background and the particles (*especially when gray color particles are used*).

- ***Applying suspended magnetic particles*** - The suspension is gently sprayed or flowed over the surface of the part. Usually, the stream of suspension is diverted from the part just before the magnetizing field is applied.

- ***Applying the magnetizing force*** - The magnetizing force should be applied immediately after applying the suspension of magnetic particles. When using a wet horizontal inspection unit, the current is applied in two or three short bursts (*1/2 second*) which helps to improve particle mobility.

- ***Inspection for indications*** - Look for areas where the magnetic particles are clustered. Surface discontinuities will produce a sharp indication. The indications from subsurface flaws will be less defined and lose definition as depth increases.

## Quality & Process Control

### *Particle Concentration and Condition*

*Particle Concentration*

The concentration of particles in the suspension is a very important parameter and it is checked after the suspension is prepared and regularly monitored as part of the quality system checks. Standards require concentration checks to be performed every eight hours or at every shift change.

The standard process used to perform the check requires agitating the carrier for a minimum of thirty minutes to ensure even particle distribution. A sample is then taken in a pear-shaped 100 ml centrifuge tube having a graduated stem (*1.0 ml in 0.05 ml increments for fluorescent particles, or 1.5 ml in 0.1 ml increments for visible particles*). The sample is then demagnetized so that the particles do not clump together while settling. The sample must then remain undisturbed for a period of time (*60 minutes for a petroleum-based carrier or 30 minutes for a water-based carrier*). The volume of settled particles is then read. Acceptable ranges are 0.1 to 0.4 ml for fluorescent particles and 1.2 to

2.4 ml for visible particles. If the particle concentration is out of the acceptable range, particles or the carrier must be added to bring the solution back in compliance with the requirement.

*Particle Condition*

After the particles have settled, they should be examined for brightness and agglomeration. Fluorescent particles should be evaluated under ultraviolet light and visible particles under white light. The brightness of the particles should be evaluated weekly by comparing the particles in the test solution to those in an unused reference solution that was saved when the solution was first prepared. Additionally, the particles should appear loose and not lumped together. If the brightness or the agglomeration of the particles is noticeably different from the reference solution, the bath should be replaced.

***Suspension Contamination***

The suspension solution should also be examined for contamination which may come from inspected components (*oils, greases, sand, or dirt*) or from the environment (*dust*). This examination is performed on the carrier and particles collected for concentration testing. Differences in color, layering or banding within the settled particles would indicate contamination. Some contamination is to be expected but if the foreign matter exceeds 30 percent of the settled solids, the solution should be replaced. The liquid carrier portion of the solution should also be inspected for contamination. Oil in a water bath and water in a solvent bath are the primary concerns.

***Water Break Test***

A daily water break check is required to evaluate the surface wetting performance of water-based carriers. The water break check simply involves flooding a clean surface similar to those being inspected and observing the surface film. If a continuous film forms over the entire surface, sufficient wetting agent is present. If the film of suspension breaks (*water break*) exposing the surface of the component, insufficient wetting agent is present and the solution should be adjusted or replaced.

### *Electrical System Checks*

Changes in the performance of the electrical system of a magnetic particle inspection unit can obviously have an effect on the sensitivity of an inspection. Therefore, the electrical system must be checked when the equipment is new, when a malfunction is suspected, or every six months. Listed below are the verification tests required by active standards.

#### *Ammeter Check*

It is important that the ammeter provide consistent and correct readings. If the meter is reading low, over magnetization will occur and possibly result in excessive background "noise." If ammeter readings are high, flux density could be too low to produce detectable indications. To verify ammeter accuracy, a calibrated ammeter is connected in series with the output circuit and values are compared to the equipment's ammeter values. Readings are taken at three output levels in the working range. The equipment meter is not to deviate from the calibrated ammeter more than ±10 percent or 50 amperes, whichever is greater. If the meter is found to be outside this range, the condition must be corrected.

#### *Shot Timer Check*

When a timer is used to control the shot duration, the timer must be calibrated. Standards require the timer be calibrated to within ± 0.1 second. A certified timer should be used to verify the equipment timer is within the required tolerances.

### *Magnetization Strength Check*

Ensuring that the magnetization equipment provides sufficient magnetic field strength is essential. Standard require the magnetization strength of electromagnetic yokes to be checked prior to use each day. The magnetization strength is checked by lifting a steel block of a standard weight using the yoke at the maximum pole spacing to be used (*10 lb weight for AC yokes or 40 lb weight for DC yokes*).

### *Lighting*

Magnetic particle inspection predominately relies on visual inspection to detect any indications that form. Therefore, lighting is a very important element of the inspection process. Obviously, the lighting requirements are different for an inspection conducted

using visible particles than they are for an inspection conducted using fluorescent particles.

*Light Requirements When Using Visible Particles*

Visible particles inspections can be conducted using natural lighting or artificial lighting. However, since natural daylight changes from time to time, the use of artificial lighting is recommended to get better uniformity. Artificial lighting should be white whenever possible (halogen lamps are most commonly used). The light intensity is required to be *100 foot-candles* (*1076 lux*) at the surface being inspected.

*Light Requirements When Using Fluorescent Particles*

*Ultraviolet Lighting*

When performing a magnetic particle inspection using fluorescent particles, the condition of the ultraviolet light and the ambient white light must be monitored. Standards and procedures require verification of lens condition and light intensity. Black lights should never be used with a cracked filter as the output of white light and harmful black light will be increased. Also, the cleanliness of the filter should also be checked regularly. The filter should be checked visually and cleaned as necessary before warming-up the light. Most UV light must be warmed up prior to use and should be on for at least *15 minutes* before beginning an inspection.

For UV lights used in component evaluations, the normally accepted intensity is *1000 $\mu W/cm^2$* at *38cm* distance from the filter face. The required check should be performed when a new bulb is installed, at startup of the inspection cycle, if a change in intensity is noticed, or every eight hours of continuous use.

*Ambient White Lighting*

When performing a fluorescent magnetic particle inspection, it is important to keep white light to a minimum as it will significantly reduce the inspector's ability to detect fluorescent indications. Light levels of less than *2 foot-candles* (*22 lux*) are required by most procedures. When checking black light intensity a reading of the white light produced by the black light may be required to verify white light is being removed by the filter.

*White Light for Indication Confirmation*

While white light is held to a minimum in fluorescent inspections, procedures may require that indications be evaluated under white light. The white light requirements for this evaluation are the same as when performing an inspection with visible particles. The minimum light intensity at the surface being inspected must be *100 foot-candles* (*1076 lux*).

*Light Measurement*

Light intensity measurements are made using a radiometer (*an instrument that transfers light energy into an electrical current*). Some radiometers have the ability to measure both black and white light, while others require a separate sensor for each measurement. Whichever type is used, the sensing area should be clean and free of any materials that could reduce or obstruct light reaching the sensor. Radiometers are relatively unstable instruments and readings often change considerable over time. Therefore, they should be calibrated at least every six months.

This article provides answers to the following questions, among others:

- What is the measurement principle behind ultrasonic testing?
- What is the coupling agent used for?
- How are ultrasound waves generated and received?
- What is the difference between longitudinal waves and transverse waves?
- What types of ultrasonic probes are used?
- What is the dead zone?
- Which probes are used for weld inspection?
- What are phased array probes and what special advantages do they offer?
- What is the minimum size of imperfections that can be detected by ultrasonic waves?



# Introduction

Ultrasonic testing is a non-destructive testing technique because the workpieces or components to be tested are not damaged during the test. If there are no complaints after the test, the component can continue to be used. Ultrasonic tests are therefore often used for weld inspections.

The most common form of ultrasonic testing is based on the *pulse-echo method*. Acoustic waves in the ultrasonic range with typical frequencies between 0.2 MHz and 100 MHz are induced pulse-like into the workpiece to be tested by a probe. The pulse duration is usually a few microseconds. These sound pulses propagate in the workpiece with characteristic sound velocity (depending on the material). At locations where the propagation speed of the ultrasonic pulses changes, the sound waves are reflected. This is then referred to as an *echo*.

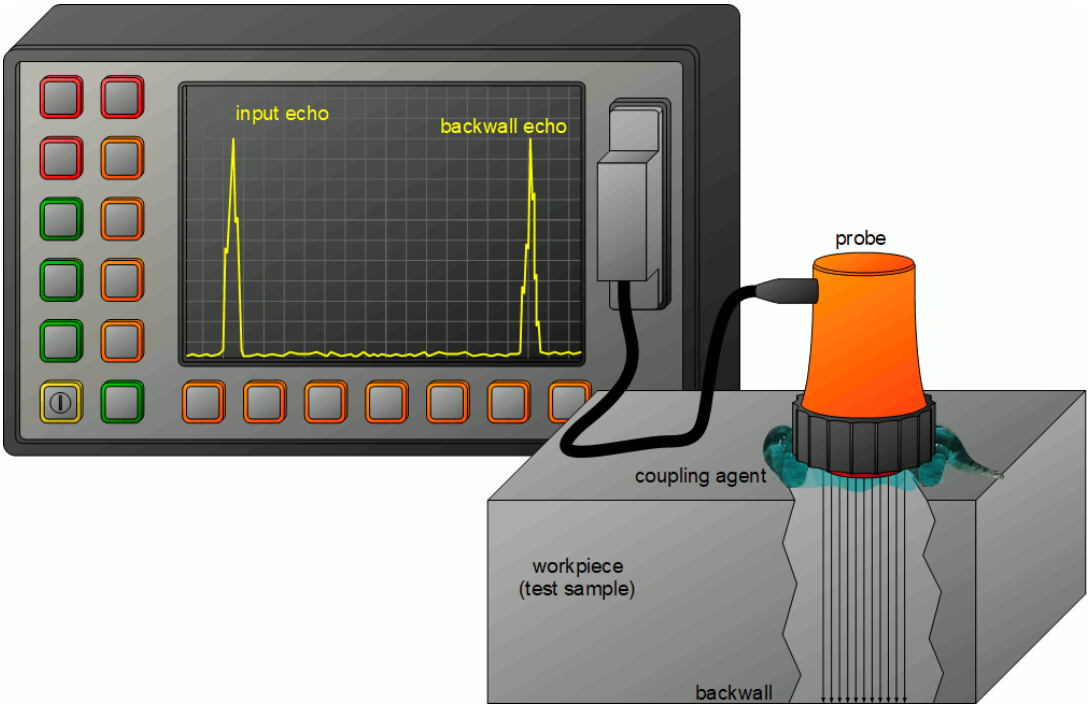



*Figure: Principle of ultrasonic testing*

Echoes occur particularly at imperfections such as pores, cavities or cracks, since the speed of sound in the metal structure is approximately 10 to 20 times higher than that of air. Such reflection points are also referred to as *reflectors.* In contrast to *flaw echos* (or *defect echos*), reflections also occur on the rear wall of the test material (*backwall echo)*.

The sound pulses reflected from the backwall or from imperfections are registered by a receiver. From the elapsed time between emission of a sound pulse and registration of a flaw echo, the location (depth) of the echo point and thus the position of the imperfection can be determined, provided that the propagation speed of the sound waves is known (depending on the material). It should be noted that the measured time results from twice the distance until the echo location is reached, since the sound pulse needs the same time for the return path after reflection.

In ultrasonic testing, sound pulses are passed through the workpiece, which are reflected at imperfections (flaw echo). In this way, defects can non-destructively be localized!

In order that the probe can induce the ultrasonic pulses into the workpiece and the entire sound pulses are not already reflected on the outside of the test material (*input echo*), the entire area of the probe must rest completely on the workpiece surface. However, due to the surface roughness of each workpiece or probe, this is not easily possible. For this reason, a gel-like *coupling agent* is applied to the workpiece. This completely wets the surface of the probe and the workpiece, thus enabling the sound pulses to be emitted and received again with low reflection. In order to achieve the necessary coupling effect in special automated processes, the entire component can also be immersed in water.

Coupling agent is used to introduced the ultrasonic waves into the workpiece with low reflection and to receive them again with low reflection!

When inspecting workpieces, the probes used are particularly important and must be carefully selected depending on the application. In order to better understand the different requirements on the probes, the generation and propagation of ultrasound is described in the next sections.

## Generation and reception of ultrasound

The principle of ultrasonic generation is based on the *piezoelectric effect*. Historically, piezoelectricity was first discovered on quartz (silicon dioxide, $SiO_2$). It was found that mechanical stress (compressive or tensile stress) leads to a shift of the charge concentrations in the atomic structure of the quartz. Electric dipoles are formed, which lead to a voltage between the top and the bottom of the quartz. Not only silicon dioxide but also many other materials such as artificially produced ceramics show a piezoelectric effect. Such materials are generally referred to as *piezoelectric crystals*.

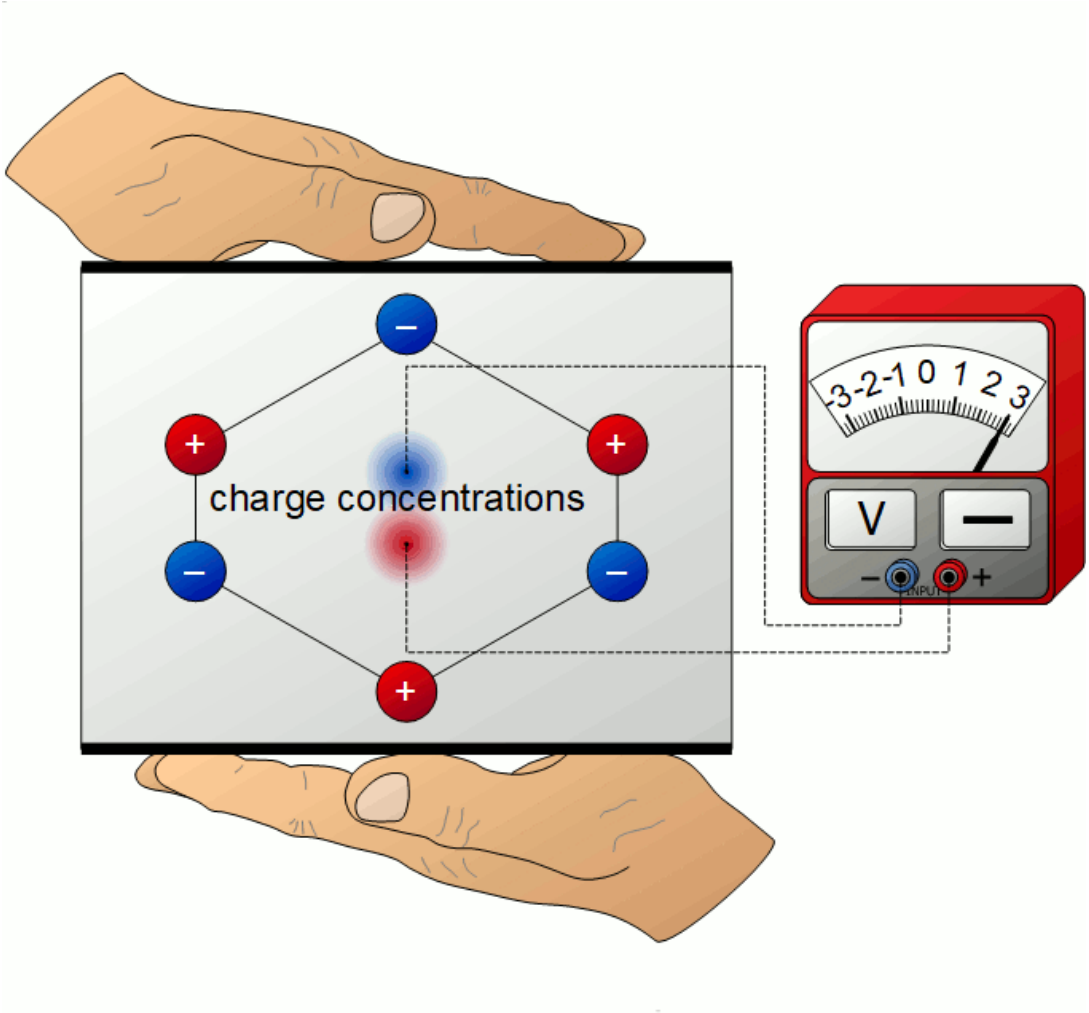
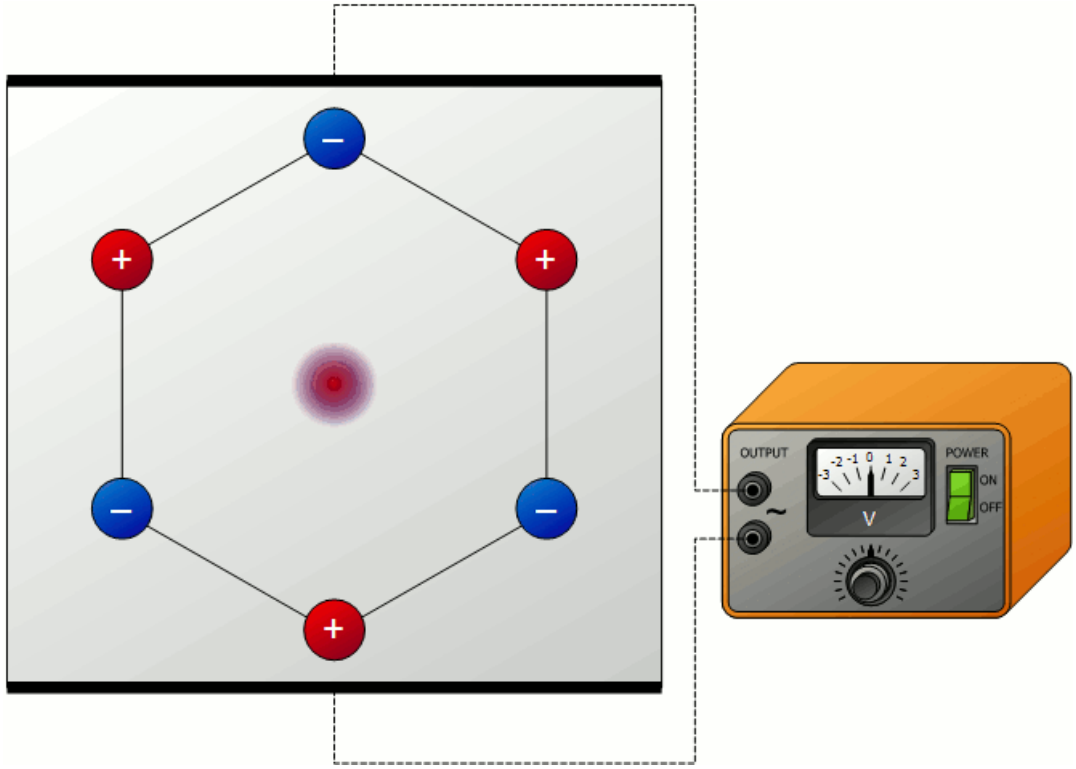



*Figure: Piezoelectric effect*

The piezoelectric effect is the generation of a voltage by mechanical deformation of certain materials (piezoelectric crystals)!

The piezoelectric effect can also be reversed! This means that when an external voltage is applied, the crystal is deformed. Depending on the polarity, the piezoelectric crystal is either compressed or stretched. This *reciprocal piezoelectric effect* (or *indirect piezoelectric effect*) can therefore be used to convert electrical energy into mechanical energy.

If an alternating voltage is applied to a piezoelectric crystal, the compressive and tensile stresses alternate permanently. As a result, the crystal oscillates. The forced oscillation frequency goes hand in hand with the frequency of the alternating voltage. This forced oscillation is particularly strong when the AC voltage frequency corresponds to the *natural frequency* of the crystal. In such a case resonance occurs and the piezoelectric crystal oscillates at maximum. The natural frequency of the crystal depends mainly on its geometry. Thus, the natural frequency of the crystal can be adjusted to the desired value by changing the geometry.




*Animation: Piezoelectric crystal on an alternating voltage*

When exposed to an alternating voltage, the piezoelectric crystal oscillates like a diaphragm of a loudspeaker, and transmits these oscillations either to the surrounding air or, as in the case of ultrasonic testing, to the component to be tested. In this case, the piezoelectric crystal serves as a transmitter of (ultra)sonic waves.

By applying a high-frequency alternating voltage to a piezoelectric crystal, it carries out vibrations in the ultrasonic range and thus serves as a transmitter of ultrasonic waves!

Piezoelectric crystals can also serve as a receiver of sound waves. When sound waves hit the piezoelectric crystal, they cause compressive and/or tensile stresses inside (in the same way that the human eardrum is stimulated by sonic wave). The electrical voltage connected to the deformation serves directly as a receive signal. Piezoelectric crystals therefore serve both to generate and to receive ultrasonic waves.

## Propagation of ultrasound

Depending on the medium, sound waves can propagate in different ways. In gaseous, liquid or solid materials, sound waves can propagate in the form of pressure fluctuations. The matter particles are compressed locally (“positive pressure”) and dilated (“negative pressure”) and transfer the corresponding impulse to the adjacent particles. The oscillation direction of the individual particles is identical to the direction of propagation of the wave. In this case one also speaks of *longitudinal waves* (also called *compressional wave* or *compression wave*).

In longitudinal waves, the individual particles oscillate longitudinally to the direction of wave propagation!

Besides the longitudinal wave propagation, there is another possibility of sound propagation in solids. In addition to compaction or dilution, the material can also undergo a “lateral” displacement (analogous to the swinging up and down of a rope). Such a lateral displacement has an effect on the adjacent particles, which also experience a force directed sideways and are thus gradually made to oscillate. In this case, the oscillation direction of the individual particles is perpendicular to the direction of the wave propagation. Such a wave is referred to as s a *transverse wave* (*shear wave*).

In transverse waves (shear waves), the individual particles oscillate transversely to the direction of wave propagation.

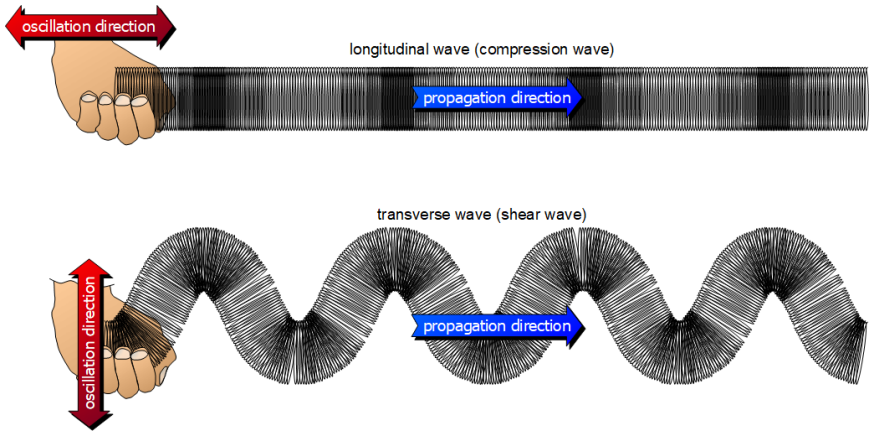



*Figure: Wave types*

Transverse waves can only propagate in media in which the individual particles are elastically connected to their neighboring particles by binding forces. Only then can the individual particles “entrain” the neighbouring particles as they move up and down. Consequently, this only applies to solids, as there are sufficient intermolecular binding forces compared to liquids and gases.

In solids, sound can propagate both as longitudinal wave and as transverse wave; in liquids and gases, however, only as longitudinal wave.

The propagation velocity of a sonic wave is called *speed of sound*. The speed of sound depends primarily on the medium in which the sound propagates. The velocity at which the individual particles oscillate back and forth (called *particle velocity*) has no influence on the propagation velocity of the wave. The particle velocity only determines the frequency of the sound wave. However, this does not cause the wave to propagate faster or slower. Strictly speaking, the speed of sound also depends on the temperature of the medium. In the case of solids, it must also be taken into account whether the sound wave propagates as longitudinal or transversal wave.

The speed of sound depends mostly on the medium in which it propagates!

## Ultrasonic probes

The principle of emitting and receiving ultrasonic waves is technically implemented in *ultrasonic probes*. Different probes have developed depending on the application. The most important ones will be discussed in more detail in the following sections.

### Normal probes

The simplest type of probes are so-called *normal probes*. These probes have only one single *piezoelectric element* (*transducer*), which is switched alternately as transmitter and receiver.

*Figure: Normal probe*

During the emission of an ultrasonic pulse, reception is basically not possible. Only when the ultrasonic pulse has been fully transmitted, the piezoelectric element can be switched back to the receive mode after a short damping period of the oscillating piezoelectric crystal. During this period of time, the emitted ultrasonic pulse has already propagated in the test material and may have already been reflected at imperfections. However, the probe could not receive these reflected waves at all, since the probe was not yet switched to “receive mode”.

This period of time within which no signal can be received is also referred to as *dead time*. The dead time is composed of the transmission time of an ultrasonic pulse and the damping time until the oscillations of the piezoelectric crystal have settled before the probe can be switched to receive mode. In connection with the speed of sound, the dead time results in a so-called *dead zone* below the workpiece surface. Imperfections within this dead zone cannot be detected by the probe.

Normal probes alternately transmit and receive ultrasonic waves; they are not suitable for testing near-surface imperfections due to the resulting “dead zone”!

To keep the dead zone to a minimum, the probe should switch to receive mode as quickly as possible after emitting the ultrasonic pulses. For this the vibrating piezoelectric crystal must be strongly damped after the emission. For this reason, a

*damping block* (*backing*) is located at the rear of the crystal, which stops the vibrations as quickly as possible after the emitting pulse. At the same time, oscillations of the entire probe (due to sound waves radiated from the rear of the piezoelectric element) is avoided.

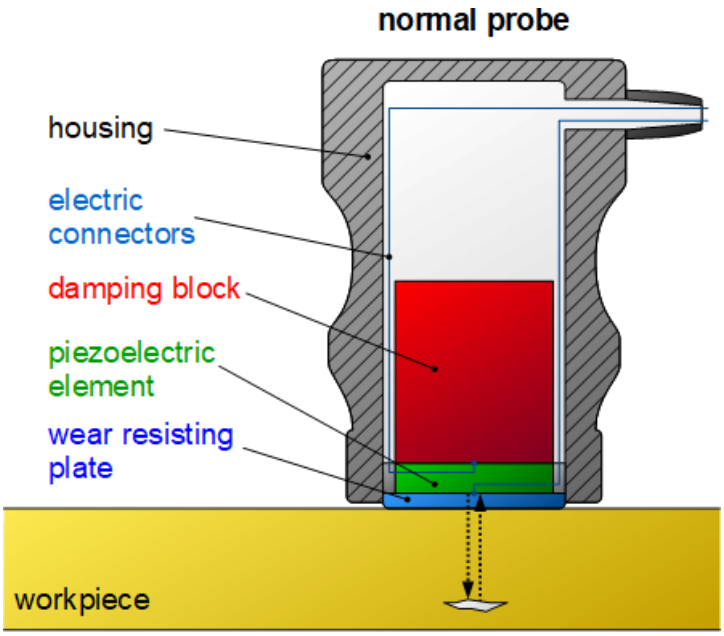



*Figure: Components of a normal probe*

As mechanical protection, the piezoelectric crystal is separated from the workpiece surface or from the applied coupling agent by a *wear resisting plate*. This protection layer prevents damage to the piezoelectric element during ultrasonic testing. In addition to the coupling agent, the wear resisting plate itself provides good sound coupling to the workpiece. Probes for smooth workpiece surfaces are usually equipped with harder (more wear-resistant) protective layers, while for rough surfaces rather softer (less sound dissipative) protective layers are used.

## Delay line probes

The normal probes cause a relatively large dead zone just below the workpiece surface. However, a high resolution near the surface is indispensable when inspecting near-surface imperfections or when measuring layer thicknesses.

For this reason, probes can be equipped with an integrated *delay line* that largely shifts the dead zone out of the test material. In this context one also speaks of *delay line probes* oder *delay line transducers*. The delay line is made of sound-conductive plastic. A *matching layer* is located between the piezoelectric element and the delay line. This ensures good sound transmission with good damping properties at the same time, so that a separate damping block can often be omitted.

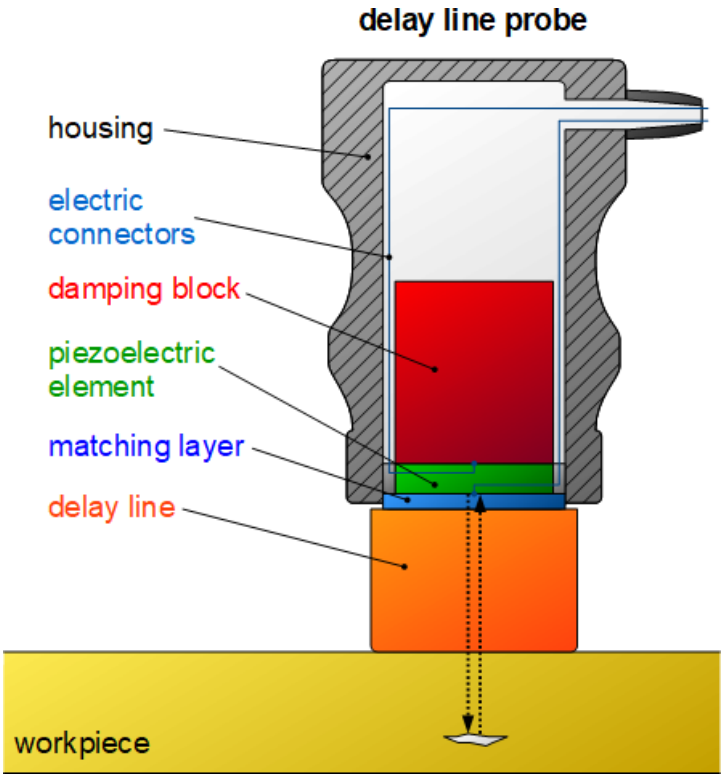



*Figure: Components of a delay line probe*

Delay line transducers have an integrated delay line within which the “dead zone” is shifted out of the workpiece surface and thus also near-surface imperfections can be detected!

When using delay line probes, reflections always occur when the emitted beam enters or leaves the the delay line. This can lead to unfavorable signal overlaps with a possible flaw echo. For this reason, the TR-probes described below have been developed.

## Transmitter-Receiver probes (TR probes)

In ***T****ransmitter-****R****eceiver probes* (*TR probes* for short), transmitter and receiver are integrated at once and acoustically separated from each other by a sound barrier. These probes can be used to transmit and receive simultaneously by separate control units. Due to the acoustic barrier, the transmitting pulse does not leave a disturbing echo for the receiver from the delay line. This enables the detection of near-surface imperfections and the measurement of thin wall thicknesses.

*Figure: Transmitter-receiver probe (TR probe)*

So that a flaw echo does not occur at the transmitter but can be detected at the receiver, the sound pulse must be radiated slightly obliquely into the workpiece. This is the only way that the flaw echo can reach the spatially separated receiver again at an angle. For this reason, the transmitter and receiver are slightly tilted towards each other. However, a dead zone forms, within which the flaw echoes are reflected past the receiver. The more the transmitter and receiver are tilted, the smaller the dead zone becomes, but deeper imperfections cannot be resolved as well.

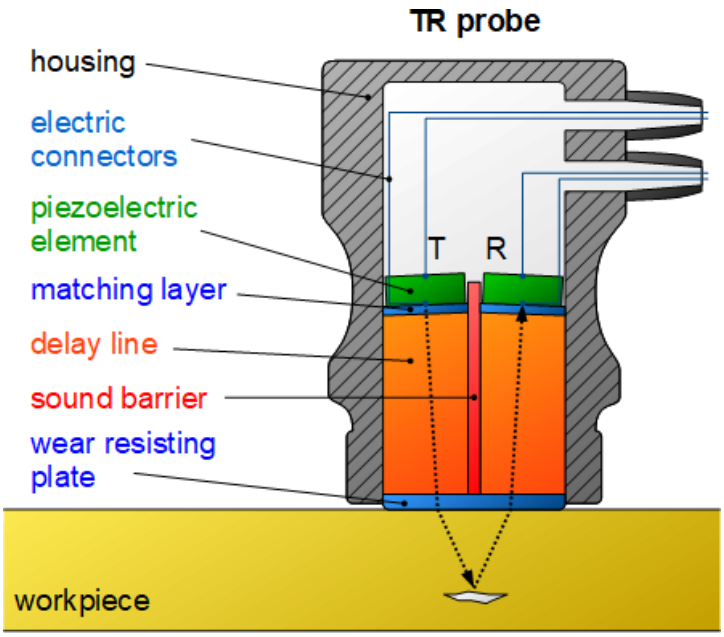



*Figure: Components of a TR probe*

The depth of the maximum resolution lies at the intersection of the acoustic axes of the transmitter and receiver. This is where the measurement sensitivity is greatest. At a relatively steep inclination, the greatest measurement sensitivity is therefore very close to the surface and the dead zone is relatively small. However, due to the small overlap of the sound paths, the sensitivity decreases considerably at deviating depths. A good resolution over longer distances can be achieved by smaller angles of inclination, but this increases the dead zone.

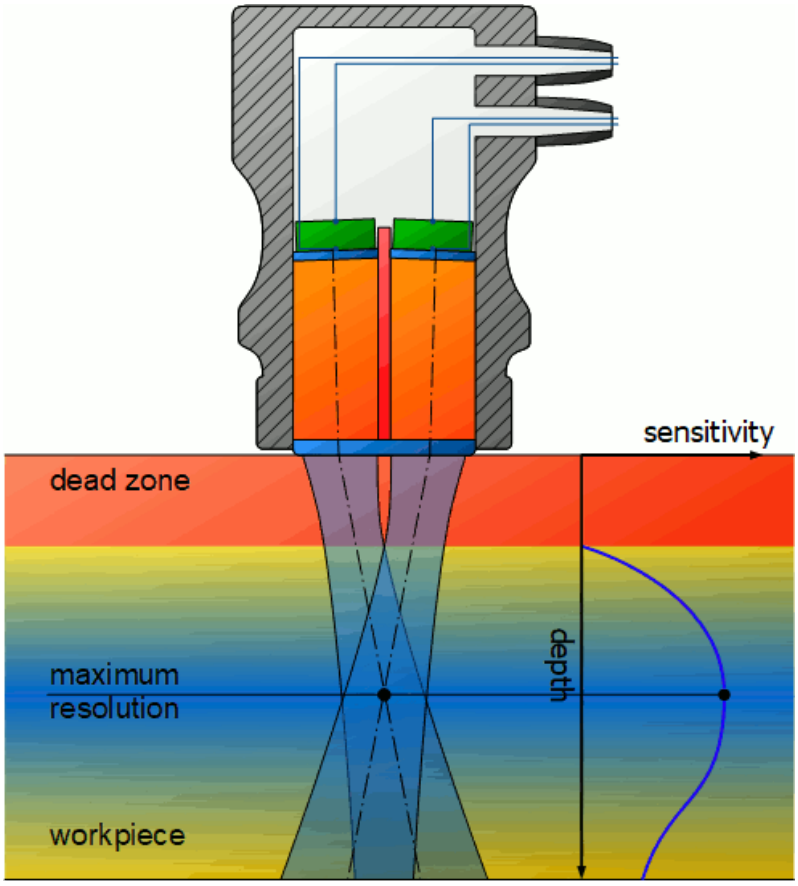



*Figure: Dead zone and sensitivity of a TR probe*

Transmit-Receive probes (TR probes) can transmit and receive ultrasonic waves simultaneously. Depending on the inclination of transmitter and receiver, the measurement sensitivity can be optimized to a certain depth!

When determining the flaw depth, it should be noted that TR probes cause a V-shaped sound path in the workpiece. The sound path and propagation time of the ultrasonic signal are therefore greater for TR probes than for normal probes. Furthermore, it should be noted that, due to the inclined intromission of sound, refraction occurs at the interface to the test material, i.e. the incident beam changes its direction as soon as the sound wave enters the workpiece (refraction is a general phenomenon of waves when penetrating a medium with a changed propagation velocity)!

## Angle probes

The inspection of weld seams requires an oblique intromission of sound so that the interface between weld seam and base material can be examined for cracks. For this reason, *angle probes* were developed which radiate the sound waves into the workpiece at a certain angle. Frequently used intromission angles are 45°, 60° and 70°.

Angle probes are particularly suitable for the inspection of weld seams due to the oblique scanning!


*Figure: Angle probe*

In general, angle probes are equipped with delay lines, which are then also referred to as *delay wedges*. Angle probes can also be equipped with TR probes, so-called *angle transmit-receive probes (angle TR probe).*

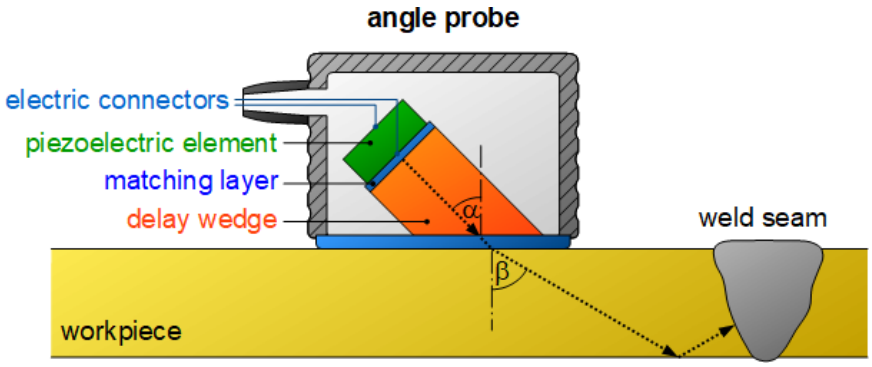



*Figure: Components of an angle probe*

In addition, a change in angle by refraction is connected to the inclined intromission of sound. Since the emitted sound waves usually propagate slower in the delay wedge (or in the wear resisting plate) than in the workpiece, a refraction away from the normal of the boundary takes place. Furthermore, the sound wave no longer propagates as a longitudinal wave but as a transverse wave. The longitudinal wave component is totally reflected at the boundary due to the greatly differing propagation velocity.

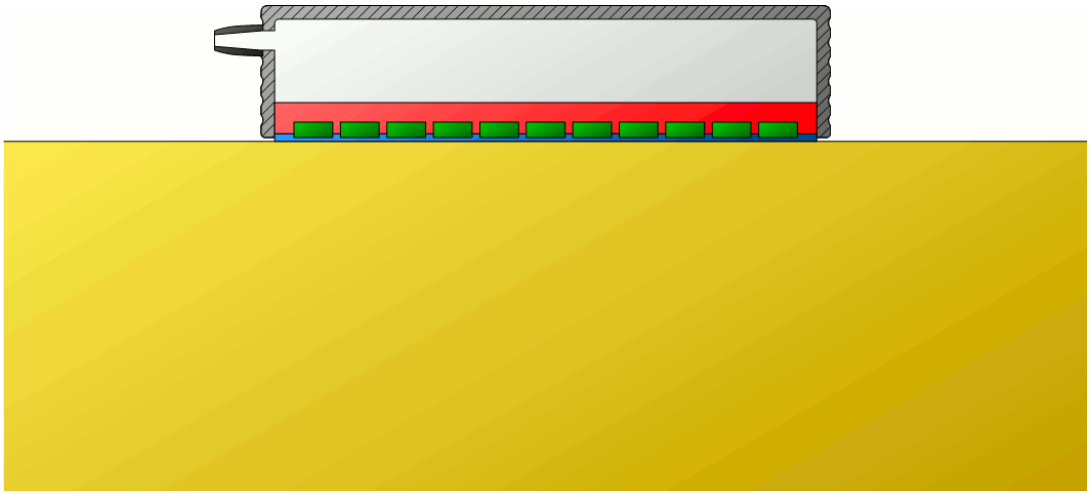
## Phased array probes

Phased array probes are basically made up of a multitude of individual transducers. Such probes are therefore also referred to as *group transducers*. In a group there are e.g. 16, 32, 64 or more oscillators. The individual transducers can be controlled separately in time. This allows a wide range of applications since the transmission characteristics can be specifically influenced. Phased array probes can only be used with special testing devices that have the appropriate software and hardware to control the probes.

Phased array probes contain a large number of individually controllable transducers. This allows the transmission characteristic to be specifically influenced!

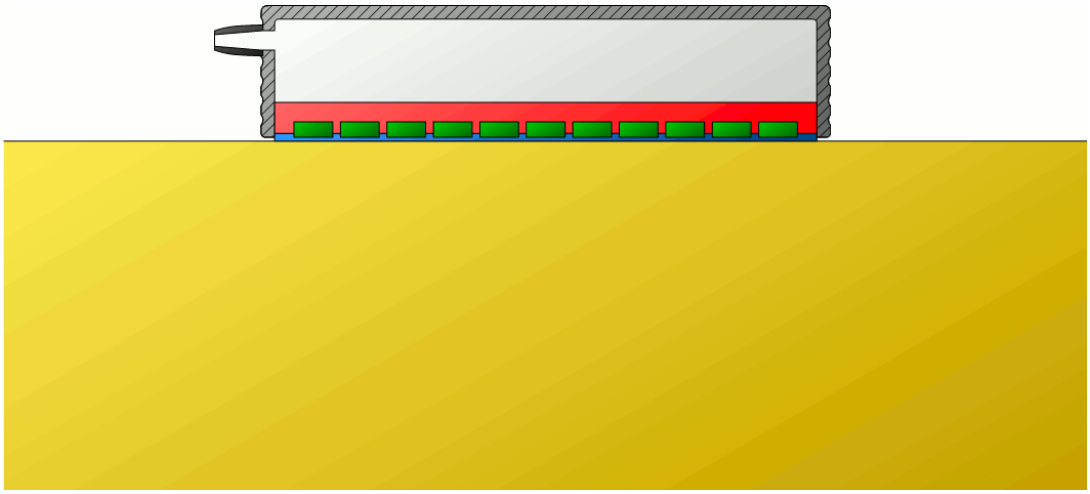
The basis for influencing the transmission characteristic is *Huygens principle*, which states that the envelopes of the individual ultrasonic waves form the new wave front.

The animations below show different timing controls. If the transducers are controlled one after the other, an angular acoustic irradiation is obtained. The sound field can also be permanently swivelled during the test. The flaw (also called *discontinuity*) then becomes visible at different angles and allows a limited indication of the flaw size. This is usually not easily possible with simple probes.



*Animation: Phased array probe with inclined intromission of sound*

Furthermore, with phased array probes the ultrasonic waves can be focused to a certain depth. The focus can also change over time, so that it moves permanently through the test sample.



*Animation: Phased array probe with focusing*

## Advantages, disadvantages and limitations of ultrasonic testing

Ultrasonic testing is not only used for detecting flaws but also for wall thickness measurement or for measuring the layer thickness of components subject to wear. It is particularly important for weld seam inspection by using an angle probe. Ultrasonic testing can be easily automated and, in comparison to the X-ray process, carried out without protective equipment. Test depths of several meters are theoretically possible depending on the acoustic properties of the test sample.

In addition to the flaw detection, ultrasonic testing also takes place for wall thickness and layer thickness measurements!

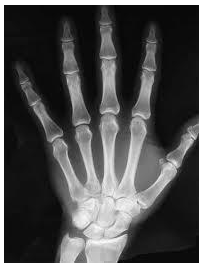
Although the position of a flaw can be determined very reliably with ultrasonic testing, the flaw size cannot be determined easily. A laminar flaw should be scanned as perpendicular as possible in order to be able to resolve it optimally. In order to estimate at least the approximate flaw dimension, the flaw should be scanned from different angles. The resulting flaw echo can then be compared with the echoes of reference flaws. Phased array probes can perform this function of the different beam angles to a limited extent. However, such a comparison method does not provide a 100% reliable statement.

Depending on the spatial orientation of the flaws, they are difficult to detect. Likewise, the flaw size is usually not clearly determinable!

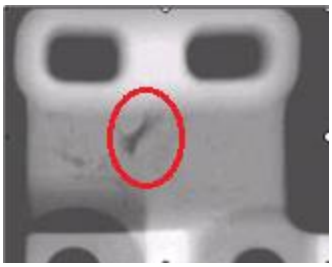
The resolution of possible flaws is limited depending on the ultrasonic frequency used. Flaws that are smaller than half the wavelength of the ultrasonic pulses can no longer be physically resolved. As the wavelength decreases with increasing frequency, smaller flaws can therefore only be resolved by higher sound frequencies. However, the higher the frequency, the higher the sound absorption, so that the high-frequency ultrasonic pulses may not be able to reach deeper flaws.

Only flaws that are larger than half the wavelength of the ultrasonic waves can be physically resolved!

# Radiographic Testing



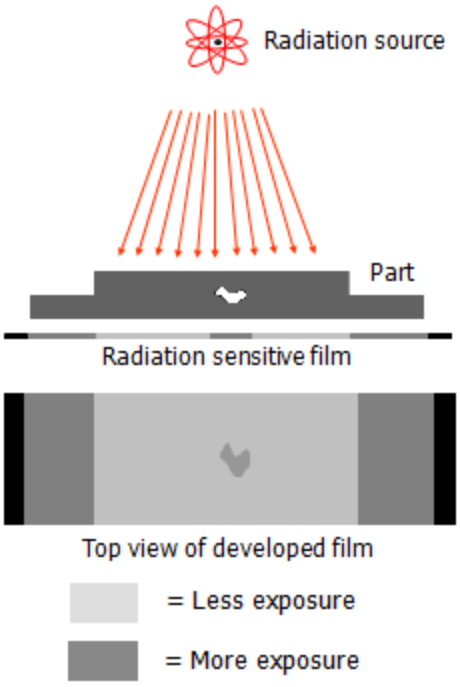
Radiography is used in a very wide range of aplications including medicine, engineering, forensics, security, etc. In NDT, radiography is one of the most important and widely used methods. Radiographic testing (RT) offers a number of advantages over other NDT methods, however, one of its major disadvantages is the health risk associated with the radiation.



In general, RT is method of inspecting materials for hidden flaws by using the ability of short wavelength electromagnetic radiation (high energy photons) to penetrate various materials. The intensity of the radiation that penetrates and passes through the material is either captured by a radiation sensitive film (*Film Radiography*) or by a planer array of radiation sensitive sensors (*Real-time Radiography*). Film radiography is the oldest approach, yet it is still the most widely used in NDT.

## Basic Principles

In radiographic testing, the part to be inspected is placed between the radiation source and a piece of radiation sensitive film. The radiation source can either be an X-ray machine or a radioactive source (*Ir-192, Co-60, or in rare cases Cs-137*). The part will stop some of the radiation where thicker and more dense areas will stop more of the radiation. The radiation that passes through the part will expose the film and forms a shadowgraph of the part. The film darkness (*density*) will vary with the amount of radiation reaching the film through the test object where darker areas indicate more exposure (*higher radiation intensity*) and lighter areas indicate less exposure (low*er radiation intensity*).




This variation in the image darkness can be used to determine thickness or composition of material and would also reveal the presence of any flaws or discontinuities inside the material.

## Advantages and Disadvantages

The primary advantages and disadvantages as compared to other NDT methods are:

*Advantages*

- Both surface and internal discontinuities can be detected.
- Significant variations in composition can be detected.
- It has a very few material limitations.
- Can be used for inspecting hidden areas (*direct access to surface is not required*)
- Very minimal or no part preparation is required.
- Permanent test record is obtained.
- Good portability especially for gamma-ray sources.

*Disadvantages*

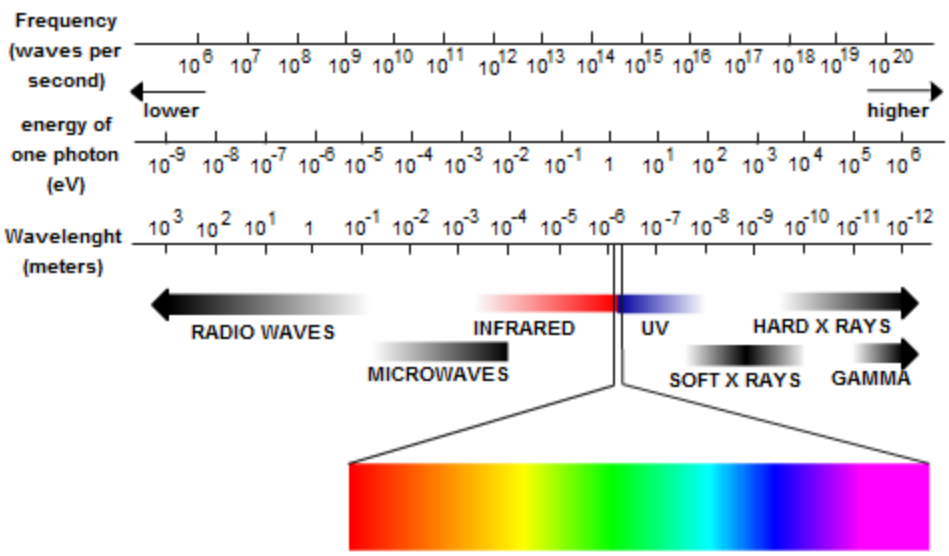
- Hazardous to operators and other nearby personnel.
- High degree of skill and experience is required for exposure and interpretation.
- The equipment is relatively expensive (*especially for x-ray sources*).
- The process is generally slow.
- Highly directional (*sensitive to flaw orientation*).
- Depth of discontinuity is not indicated.
- It requires a two-sided access to the component.

# *PHYSICS OF RADIATION*

## Nature of Penetrating Radiation

Both X-rays and gamma rays are electromagnetic waves and on the electromagnetic spectrum they ocupy frequency ranges that are higher than ultraviolate radiation. In terms of frequency, gamma rays generaly have higher frequencies than X-rays as seen in the figure. The major distenction between X-rays and gamma rays is the origion where X-rays are usually artificially produced using an X-ray generator and gamma radiation is the product of radioactive materials. Both X-rays and gamma rays are waveforms, as are light rays, microwaves, and radio waves. X-rays and gamma rays cannot been seen, felt, or heard. They possess no charge and no mass and, therefore,

are not influenced by electrical and magnetic fields and will generally travel in straight lines. However, they can be diffracted (bent) in a manner similar to light.




**The Electromagnetic Spectrum**

Electromagentic radiation act somewhat like a particle at times in that they occur as small "packets" of energy and are referred to as "*photons*". Each photon contains a certain amount (*or bundle*) of energy, and all electromagnetic radiation consists of these photons. The only difference between the various types of electromagnetic radiation is the amount of energy found in the photons. Due to the short wavelength of X-rays and gamma rays, they have more energy to pass through matter than do the other forms of energy in the electromagnetic spectrum. As they pass through matter, they are scattered and absorbed and the degree of penetration depends on the kind of matter and the energy of the rays.

***Properties of X-Rays and Gamma Rays***

- They are not detected by human senses (cannot be seen, heard, felt, etc.).
- They travel in straight lines at the speed of light.
- Their paths cannot be changed by electrical or magnetic fields.
- They can be diffracted, refracted to a small degree at interfaces between two different materials, and in some cases be reflected.
- They pass through matter until they have a chance to encounter with an atomic particle.
- Their degree of penetration depends on their energy and the matter they are traveling through.
- They have enough energy to ionize matter and can damage or destroy living cells.

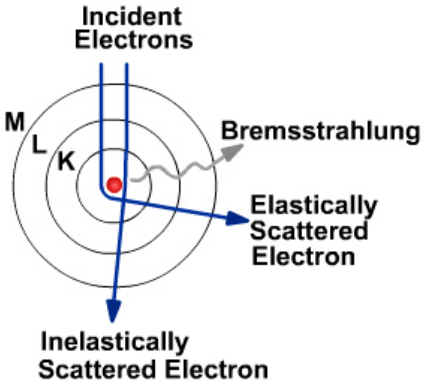
## X-Radiation

X-rays are just like any other kind of electromagnetic radiation. They can be produced in packets of energy called photons, just like light. There are two different atomic processes that can produce X-ray photons. One is called *Bremsstrahlung* (*a German term meaning "braking radiation"*) and the other is called *K-shell emission*. They can both occur in the heavy atoms of tungsten which is often the material chosen for the target or anode of the X-ray tube.

Both ways of making X-rays involve a change in the state of electrons. However, Bremsstrahlung is easier to understand using the classical idea that radiation is emitted when the velocity of the electron shot at the tungsten target changes. The negatively charged electron slows down after swinging around the nucleus of a positively charged tungsten atom and this energy loss produces X-radiation. Electrons are scattered elastically or inelastically by the positively charged nucleus. The inelastically scattered electron loses energy, and thus produces X-ray photon, while the elastically scattered electrons generally change their direction significantly but without loosing much of their energy.

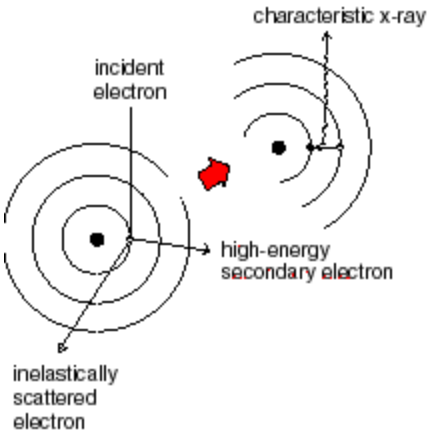
### *Bremsstrahlung Radiation*

X-ray tubes produce X-ray photons by accelerating a stream of electrons to energies of several hundred kiloelectronvolts with velocities of several hundred kilometers per hour and colliding them into a heavy target material. The abrupt deceleration of the charged particles (electrons) produces Bremsstrahlung photons. X-ray radiation with a continuous spectrum of energies is produced with a range from a few *keV* to a maximum of the energy of the electron beam.




The Bremsstrahlung photons generated within the target material are attenuated as they pass through, typically, 50 microns of target material. The beam is further attenuated by the aluminum or beryllium vacuum window. The results are the elimination of the low energy photons, *1 keV* through *15 keV*, and a significant reduction in the portion of the spectrum from *15 keV* through *50 keV*. The spectrum from an X-ray tube is further modified by the filtration caused by the selection of filters used in the setup.

### *K-shell Emission Radiation*




Remember that atoms have their electrons arranged in closed "shells" of different energies. The K-shell is the lowest energy state of an atom. An incoming electron can give a K-shell electron enough energy to knock it out of its energy state. About *0.1%* of the electrons produce K-shell vacancies; most produce heat. Then, a tungsten electron of higher energy (from an outer shell) can fall into the K-shell. The energy lost by the falling electron shows up as an emitted X-ray photon. Meanwhile, higher energy electrons fall into the vacated energy state in the outer shell, and so on. After losing an electron, an atom remains ionized for a very short time (about $10^{-14}$ second) and thus an atom can be repeatedly ionized by the incident electrons which arrive about every $10^{-12}$ second. Generally, K-shell emission produces higher-intensity X-rays than Bremsstrahlung, and the X-ray photon comes out at a single wavelength.

## Gamma Radiation

Gamma radiation is one of the three types of natural radioactivity. Gamma rays are electromagnetic radiation just like X-rays. The other two types of natural radioactivity are alpha and beta radiation, which are in the form of particles. Gamma rays are the most energetic form of electromagnetic radiation.

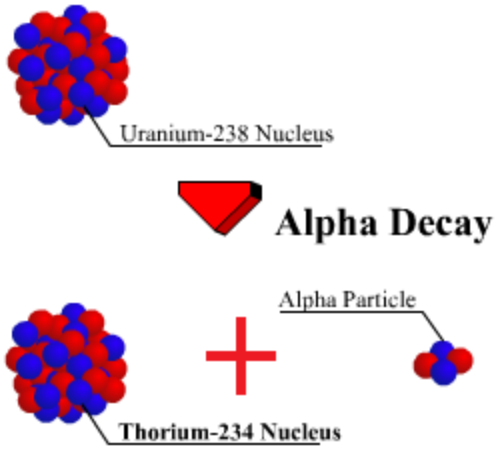
Gamma radiation is the product of radioactive atoms. Depending upon the ratio of neutrons to protons within its nucleus, an isotope of a particular element may be stable or unstable. When the binding energy is not strong enough to hold the nucleus of an atom together, the atom is said to be unstable. Atoms with unstable nuclei are constantly changing as a result of the imbalance of energy within the nucleus. Over time, the nuclei of unstable isotopes spontaneously disintegrate, or transform, in a process known as "*radioactive decay*" and such material is called "*radioactive material*".

### *Types of Radiation Produced by Radioactive Decay*

When an atom undergoes radioactive decay, it emits one or more forms of high speed subatomic particles ejected from the nucleus or electromagnetic radiation (gamma-rays) emitted by either the nucleus or orbital electrons.

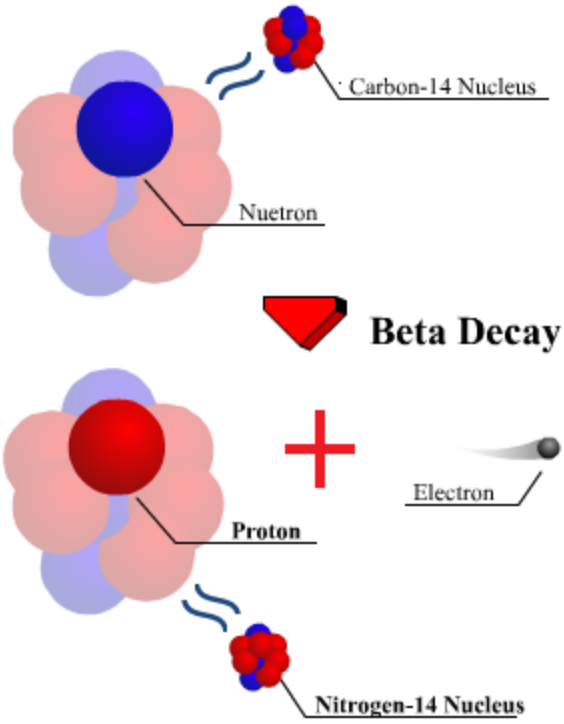
*Alpha Particles*

Certain radioactive materials of high atomic mass (*such as Ra-226, U-238, Pu-239*), decay by the emission of alpha particles. These alpha particles are tightly bound units of two neutrons and two protons each (*He-4 nucleus*) and have a positive charge. Emission of an alpha particle from the nucleus results in a decrease of two units of atomic number (*Z*) and four units of mass number (*A*). Alpha particles are emitted with discrete energies characteristic of the particular transformation from which they originate. All alpha particles from a particular radionuclide transformation will have identical energies.




*Beta Particles*

A nucleus with an unstable ratio of neutrons to protons may decay through the emission of a high speed electron called a beta particle. In beta decay a neutron will split into a positively charged proton and a negatively charged electron. This results in a net change of one unit of atomic number (*Z*) and no change in the mass number (*A*). Beta particles have a negative charge and the beta particles emitted by a specific radioactive material will range in energy from near zero up to a maximum value, which is characteristic of the particular transformation.

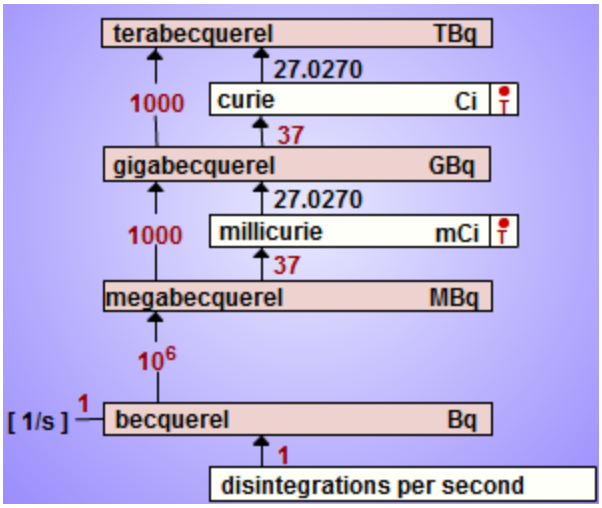



*Gamma-rays*

A nucleus which is in an excited state (*unstable nucleus*) may emit one or more photons of discrete energies. The emission of gamma rays does not alter the number of protons or neutrons in the nucleus but instead has the effect of moving the nucleus from *a higher to a lower energy state* (*unstable to stable*). Gamma ray emission frequently follows beta decay, alpha decay, and other nuclear decay processes.

## Activity (*of Radioactive Materials*)

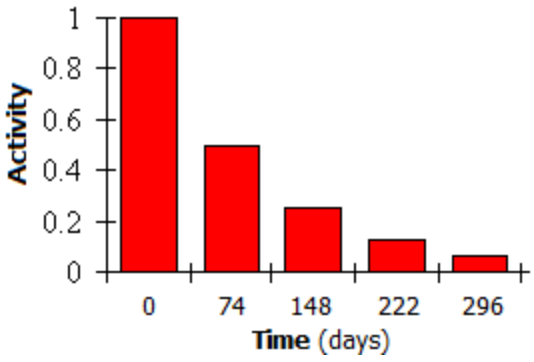
The quantity which expresses the radiation producing potential of a given amount of radioactive material is called "*Activity*". The *Curie* (***Ci***) was originally defined as that amount of any radioactive material that disintegrates at the same rate as one gram of pure radium. The International System (SI) unit for activity is the *Becquerel* (***Bq***), which is that quantity of radioactive material in which one atom is transformed per second. The radioactivity of a given amount of radioactive material does not depend upon the mass of material present. For example, two one-curie sources of the same radioactive material might have very different masses depending upon the relative proportion of non-radioactive atoms present in each source.




The concentration of radioactivity, or the relationship between the mass of radioactive material and the activity, is called "*specific activity*". Specific activity is expressed as the number of *Curies* or *Becquerels* per unit mass or volume. Each gram of Cobalt-60 will contain approximately *50 Ci*. Iridium-192 will contain *350 Ci* for every gram of material. The higher specific activity of iridium results in physically smaller sources. This allows technicians to place the source in closer proximity to the film while maintaining the sharpness of the radiograph.

## Isotope Decay Rate (Half-Life)

Each radioactive material decays at its own unique rate which cannot be altered by any chemical or physical process. A useful measure of this rate is the "*half-life*" of the radioactivity. Half-life is defined as the time required for the activity of any particular radionuclide to decrease to one-half of its initial value. In other words one-half of the atoms have reverted to a more stable state material. Half-lives of radioactive materials range from microseconds to billions of years. Half-life of two widely used industrial isotopes are; *74 days for Iridium-192, and 5.3 years for Cobalt-60*.



In order to find the remaining activity of a certain material with a known half-life value after a certain period of time, the following formula may be used. The formula calculates the decay fraction (*or the remaining fraction of the initial activity*) as:

$$\boxed{f_D = \frac{A}{A_o} = (0.5)^{\frac{t}{L_H}}}$$

Where;

$f_D$ : decay fraction (i.e., remaining fraction of the initial activity)
$L_H$ : Half-Life value (*hours, days, years, etc.*)
$t$ : Elapsed time (*hours, days, years, etc.*)

Or alternatively, the equitation can be solved to find the time required for activity to decay to a certain level as:

$$\boxed{t = L_H \left(\frac{\log f_D}{\log 0.5}\right)}$$

## Radiation Energy, Intensity and Exposure

Different radioactive materials and X-ray generators produce radiation at different energy levels and at different rates. It is important to understand the terms used to describe the energy and intensity of the radiation.

### *Radiation Energy*

The energy of the radiation is responsible for its ability to penetrate matter. Higher energy radiation can penetrate more and higher density matter than low energy radiation. The energy of ionizing radiation is measured in *electronvolts* (***eV***). One electronvolt is an extremely small amount of energy so it is common to use kiloelectronvolts (***keV***) and megaelectronvolt (***MeV***). An electronvolt is a measure of energy, which is different from a volt which is a measure of the electrical potential between two positions. Specifically, an electronvolt is the kinetic energy gained by an electron passing through a potential difference of one volt. X-ray generators have a control to adjust the radiation energy, *keV* (or *kV*).

The energy of a radioisotope is a characteristic of the atomic structure of the material. Consider, for example, Iridium-192 and Cobalt-60, which are two of the more common

industrial Gamma ray sources. These isotopes emit radiation in two or three discreet wavelengths. Cobalt-60 will emit *1.17 and 1.33 MeV* gamma rays, and Iridium-192 will emit *0.31, 0.47, and 0.60 MeV* gamma rays. It can be seen from these values that the energy of radiation coming from Co-60 is more than twice the energy of the radiation coming from the Ir-192. From a radiation safety point of view, this difference in energy is important because the Co-60 has more material penetrating power and, therefore, is more dangerous and requires more shielding.

### *Intensity and Exposure*

Radiation intensity is the amount of energy passing through a given area that is perpendicular to the direction of radiation travel in a given unit of time. One way to measure the intensity of X-rays or gamma rays is to measure the amount of ionization they cause in air. The amount of ionization in air produced by the radiation is called the exposure. Exposure is expressed in terms of a scientific unit called a *Roentgen* (***R***). The unit roentgen is equal to the amount of radiation that ionizes *1 $cm^3$* of dry air (at 0°C and standard atmospheric pressure) to one electrostatic unit of charge, of either sign. Most portable radiation detection safety devices used by radiographers measure exposure and present the reading in terms of *Roentgens* or *Roentgens/hour*, which is known as the "*dose rate*".

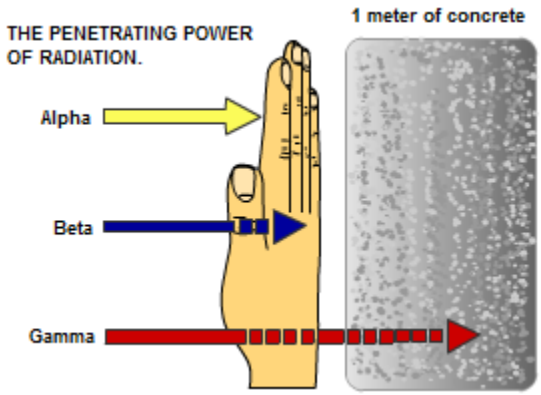
## Ionization

As penetrating radiation moves from point to point in matter, it loses its energy through various interactions with the atoms it encounters. The rate at which this energy loss occurs depends upon the type and energy of the radiation and the density and atomic composition of the matter through which it is passing.

The various types of penetrating radiation impart their energy to matter primarily through excitation and ionization of orbital electrons. The term "*excitation*" is used to describe an interaction where electrons acquire energy from a passing charged particle but are not removed completely from their atom. Excited electrons may subsequently emit energy in the form of X-rays during the process of returning to a lower energy state. The term "*ionization*" refers to the complete removal of an electron from an atom following the transfer of energy from a passing charged particle.

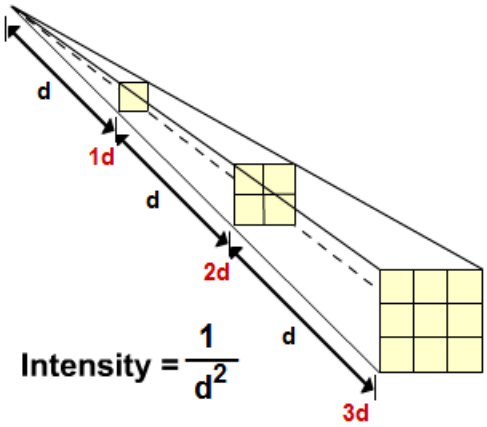
Because of their double charge and relatively slow velocity, alpha particles have a relatively short range in matter (a few centimeters in air and only fractions of a millimeter in tissue). Beta particles have, generally, a greater range.

Since they have no charge, gamma-rays and X-rays proceeds through matter until there is a chance of interaction with a particle. If the particle is an electron, it may receive enough energy to be ionized, whereupon it causes further ionization by direct interactions with other electrons. As a result, gamma-rays and X-rays can cause the liberation of electrons deep inside a medium. As a result, a given gamma or X-ray has a definite probability of passing through any medium of any depth.




## Newton's Inverse Square Law

Any point source which spreads its influence equally in all directions without a limit to its range will obey the inverse square law. This comes from strictly geometrical considerations. The intensity of the influence at any given distance (***d***) is the source strength divided by the area of a sphere having a radius equal to the distance (***d***). Being strictly geometric in its origin, the inverse square law applies to diverse phenomena. Point sources of gravitational force, electric field, light, sound, and radiation obey the inverse square law.




As one of the fields which obey the general inverse square law, the intensity of the radiation received from a point radiation source can be characterized by the diagram above. The relation between intensity and distance according to the inverse square law can be expresses as:

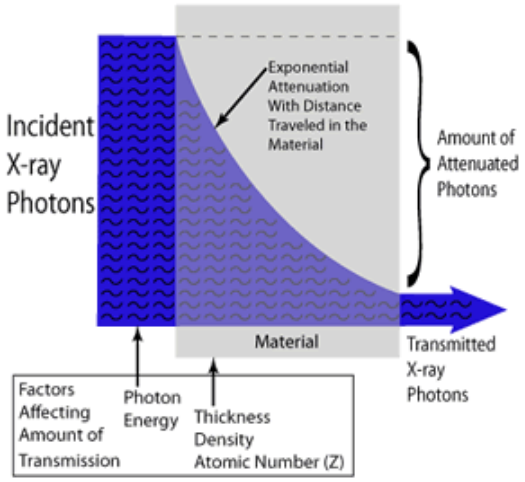
$$I_1 {d_1}^2 = I_2 {d_2}^2$$

Where $I_1$ & $I_2$ are the intensities at distances $d_1$ & $d_2$ form the source, respectively.

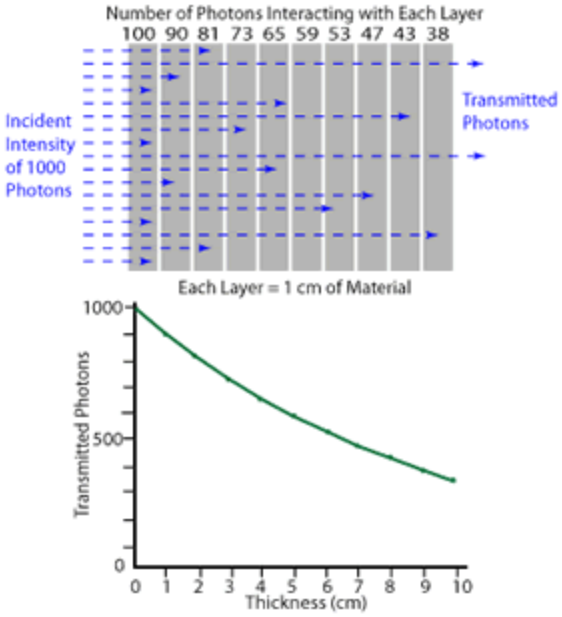
All measures of exposure or dose rate will drop off by the inverse square law. For example, if the received dose of radiation is *100 mR/hr* at *2 cm* from a source, it will be *0.01 mR/hr* at *2 m*.

## Interaction between Penetrating Radiation and Matter (*Attenuation*)

When X-rays or gamma rays are directed into an object, some of the photons interact with the particles of the matter and their energy can be absorbed or scattered. This absorption and scattering is called "*Attenuation*". Other photons travel completely through the object without interacting with any of the material's particles. The number of photons transmitted through a material depends on the thickness, density and atomic number of the material, and the energy of the individual photons.




Even when they have the same energy, photons travel different distances within a material simply based on the probability of their encounter with one or more of the particles of the matter and the type of encounter that occurs. Since the probability of an encounter increases with the distance traveled, the number of photons reaching a specific point within the matter decreases exponentially with distance traveled. As shown in the graphic to the right, if 1000 photons are aimed at ten 1 cm layers of a material and there is a 10% chance of a photon being attenuated in this layer, then there will be 100 photons attenuated. This leaves 900 photos to travel into the next layer where 10% of these photos will be attenuated. By continuing this progression, the exponential shape of the curve becomes apparent.




The formula that describes this curve is:

$$\boxed{I = I_0 e^{-\mu x}}$$

Where;

$I_0$ : initial (*unattenuated*) intensity
$\mu$ : linear attenuation coefficient per unit distance
$x$ : distance traveled through the matter

***Linear and Mass Attenuation Coefficients***

The "*linear attenuation coefficient*" ($\mu$) describes the fraction of a beam of X-rays or gamma rays that is absorbed or scattered per unit thickness of the absorber (*10% per cm thickness for the previous example*).

Using the transmitted intensity equation above, linear attenuation coefficients can be used to make a number of calculations. These include:

- The intensity of the energy transmitted through a material when the incident X-ray intensity, the material and the material thickness are known.
- The intensity of the incident X-ray energy when the transmitted X-ray intensity, material, and material thickness are known.
- The thickness of the material when the incident and transmitted intensity, and the material are known.
- The material can be determined from the value of $\mu$ when the incident and transmitted intensity, and the material thickness are known.

Linear attenuation coefficients can sometimes be found in the literature. However, it is often easier to locate attenuation data in terms of the "*mass attenuation coefficient*". Tables and graphs of the mass attenuation coefficients for chemical elements and for several compounds and mixtures as a function of radiation energy (*in* ***keV***) are available in literature (*such information can be found at the National Institute for Standards and Technology website: http://www.nist.gov/pml/data/xraycoef/* ).

Since a linear attenuation coefficient is dependent on the density of a material, the mass attenuation coefficient is often reported for convenience. Consider water for example. The linear attenuation for water vapor is much lower than it is for ice because the molecules are more spread out in vapor so the chance of a photon encounter with a water particle is less. Normalizing $\mu$ by dividing it by the density of the element or compound will produce a value that is constant for a particular element or compound. This constant ($\mu/\rho$) is known as the mass attenuation coefficient and has units of $cm^2/gm$. The mass attenuation coefficient can simply be converted to a linear attenuation coefficient by multiplying it by the density ($\rho$) of the material.

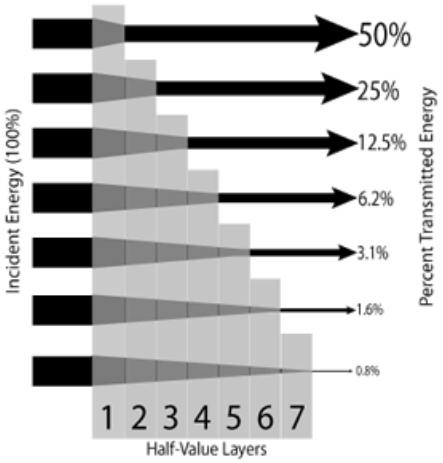
## Half-Value Layer

The thickness of any given material where 50% of the incident energy has been attenuated is known as the half-value layer (***HVL***). The *HVL* is expressed in units of distance (*mm or cm*). Like the attenuation coefficient, it is photon energy dependant. Increasing the penetrating energy of a stream of photons will result in an increase in a material's *HVL*.

The *HVL* is inversely proportional to the attenuation coefficient. If an incident energy of ***1*** and a transmitted energy of ***0.5*** are plugged into the intensity attenuation equation introduced earlier, solving for $x$ which will correspond to the *HVL* gives:

$$0.5 = 1e^{-\mu x} \quad \rightarrow \quad \boxed{HVL = \frac{0.693}{\mu}}$$

The *HVL* is often used in radiography simply because it is easier to remember values and perform simple calculations. In a shielding calculation, such as illustrated to the right, it can be seen that if the thickness of one *HVL* is known, it is possible to quickly determine how much material is needed to reduce the intensity to less than 1%.




In order to calculate the ratio of intensity attenuation (*or reduction*) resulting from passing through a certain thickness of a material for which the *HVL* is known, the following equation may be used:

$$\boxed{r_I = \frac{I}{I_o} = (0.5)^{\frac{Thickness}{HVL}}}$$

Where $r_I$ is intensity reduction ratio.

Or alternatively, the equitation can be solved to find the material thickness required for reducing the intensity to a certain level as:

$$\boxed{Thickness = HVL\left(\frac{\log r_I}{\log 0.5}\right)}$$

Sometimes instead of specifying the *HVL*, the Tenth Value Layer (*TVL*) is specified. The *TVL* is the thickness that attenuates 90% of the intensity (only 10% passes through).

In that case, the equation becomes:

$$r_I = \frac{I}{I_o} = (0.1)^{\frac{Thickness}{TVL}}$$

Approximate *HVL* for various materials when radiation is from a gamma-ray source:

| | **Half-Value Layer** (*mm*) | | | | |
|---|---|---|---|---|---|
| ***Source*** | **Concrete** | **Steel** | **Lead** | **Tungsten** | **Uranium** |
| **Iridium-192** | *44.5* | *12.7* | *4.8* | *3.3* | *2.8* |
| **Cobalt-60** | *60.5* | *21.6* | *12.5* | *7.9* | *6.9* |

Approximate *HVL* for some materials when radiation is from an X-ray source:

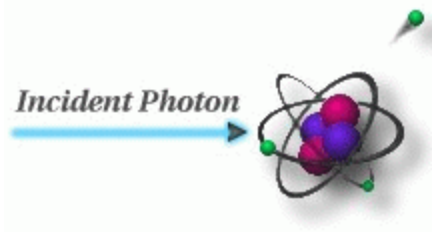
| | **Half-Value Layer** (*mm*) | |
|---|---|---|
| ***X-ray Tube Voltage*** (*kV*) | **Lead** | **Concrete** |
| **50** | *0.06* | *4.32* |
| **100** | *0.27* | *15.10* |
| **150** | *0.30* | *22.32* |
| **200** | *0.52* | *25.0* |
| **250** | *0.88* | *28.0* |
| **300** | *1.47* | *31.21* |
| **400** | *2.5* | *33.0* |
| **1000** | *7.9* | *44.45* |

## Sources of Attenuation

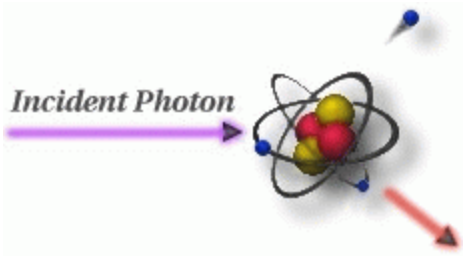
The attenuation that results due to the interaction between penetrating radiation and matter is not a simple process. A single interaction event between a primary X-ray photon and a particle of matter does not usually result in the photon changing to some other form of energy and effectively disappearing. Several interaction events are usually involved and the total attenuation is the sum of the attenuation due to different types of interactions. These interactions include the photoelectric effect, scattering, and pair production.

- *Photoelectric (**PE**) absorption* of X-rays occurs when the X-ray photon is absorbed, resulting in the ejection of electrons from the outer shell of the atom, and hence the ionization of the atom. Subsequently, the ionized atom returns to the neutral

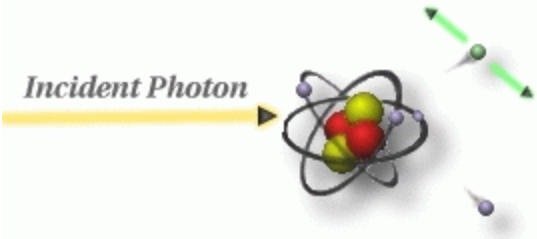
state with the emission of an X-ray characteristic of the atom. This subsequent emission of lower energy photons is generally absorbed and does not contribute to (or hinder) the image making process. Photoelectron absorption is the dominant process for X-ray absorption up to energies of about *500 keV*. Photoelectric absorption is also dominant for atoms of high atomic numbers.




- *Compton scattering (**C**)* occurs when the incident X-ray photon is deflected from its original path by an interaction with an electron. The electron gains energy and is ejected from its orbital position. The X-ray photon loses energy due to the interaction but continues to travel through the material along an altered path. Since the scattered X-ray photon has less energy, it, therefore, has a longer wavelength than the incident photon.




- *Pair production (**PP**)* can occur when the X-ray photon energy is greater than *1.02 MeV*, but really only becomes significant at energies around *10 MeV*. Pair production occurs when an electron and positron are created with the annihilation of the X-ray photon. Positrons are very short lived and disappear (positron annihilation) with the formation of two photons of *0.51 MeV* energy. Pair production is of particular importance when high-energy photons pass through materials of a high atomic number.



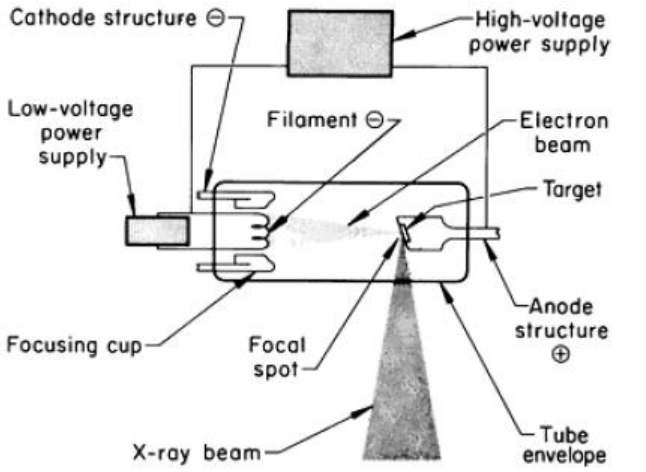

# ***EQUIPMENT & MATERIALS***

## X-ray Generators

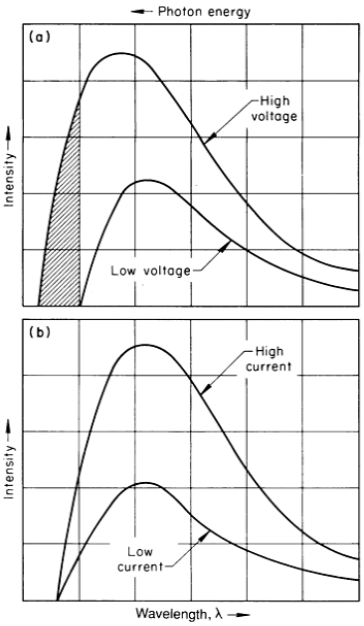
The major components of an X-ray generator are the tube, the high voltage generator, the control console, and the cooling system. As discussed earlier in this material, X-rays are generated by directing a stream of high speed electrons at a target material such as tungsten, which has a high atomic number. When the electrons are slowed or stopped

by the interaction with the atomic particles of the target, X-radiation is produced. This is accomplished in an X-ray tube such as the one shown in the figure.

The tube cathode (*filament*) is heated with a low-voltage current of a few amps. The filament heats up and the electrons in the wire become loosely held. A large electrical potential is created between the cathode and the anode by the high-voltage generator. Electrons that break free of the cathode are strongly attracted to the anode target. The stream of electrons between the cathode and the anode is the tube current. The tube current is measured in milliamps and is controlled by regulating the low-voltage heating current applied to the cathode. The higher the temperature of the filament, the larger the number of electrons that leave the cathode and travel to the anode. The milliamp or current setting on the control console regulates the filament temperature, which relates to the intensity of the X-ray output.




The high-voltage between the cathode and the anode affects the speed at which the electrons travel and strike the anode. The higher the kilovoltage, the more speed and, therefore, energy the electrons have when they strike the anode. Electrons striking with more energy result in X-rays with more penetrating power. The high-voltage potential is measured in kilovolts, and this is controlled with the voltage or kilovoltage control on the control console. An increase in the kilovoltage will also result in an increase in the intensity of the radiation. The figure shows the spectrum of the radiated X-rays associated with the voltage and current settings. The top figure shows that increasing the kV increases both the energy of X-rays and also increases the intensity of radiation (*number of photons*). Increasing the current, on the other hand, only increases the intensity without shifting the spectrum.




A focusing cup is used to concentrate the stream of electrons to a small area of the target called the "*focal spot*". The focal spot size is an important factor in the system's ability to produce a sharp image. Much of the energy applied to the tube is transformed into heat at the focal spot of the anode. As mentioned above, the anode target is commonly made from tungsten, which has a high melting point in addition to

a high atomic number. However, cooling of the anode by active or passive means is necessary. Water or oil re-circulating systems are often used to cool tubes. Some low power tubes are cooled simply with the use of thermally conductive materials and heat radiating fins.

In order to prevent the cathode from burning up and to prevent arcing between the anode and the cathode, all of the oxygen is removed from the tube by pulling a vacuum. Some systems have external vacuum pumps to remove any oxygen that may have leaked into the tube. However, most industrial X-ray tubes simply require a warm-up procedure to be followed. This warm-up procedure carefully raises the tube current and voltage to slowly burn any of the available oxygen before the tube is operated at high power.

In addition, X-ray generators usually have a filter along the beam path (*placed at or near the x-ray port*). Filters consist of a thin sheet of material (*often high atomic number materials such as lead, copper, or brass*) placed in the useful beam to modify the spatial distribution of the beam. Filtration is required to absorb the lower-energy X-ray photons emitted by the tube before they reach the target in order to produce a cleaner image (*since lower energy X-ray photons tend to scatter more*).

The other important component of an X-ray generating system is the control console. Consoles typically have a keyed lock to prevent unauthorized use of the system. They will have a button to start the generation of X-rays and a button to manually stop the generation of X-rays. The three main adjustable controls regulate the tube voltage in *kilovolts*, the tube amperage in *milliamps*, and the exposure time in *minutes and seconds*. Some systems also have a switch to change the focal spot size of the tube.

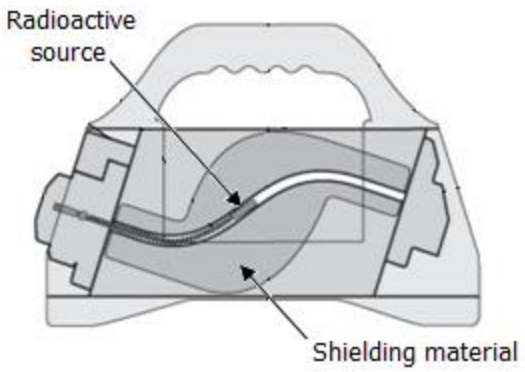
## Radio Isotope (*Gamma-ray*) Sources

Manmade radioactive sources are produced by introducing an extra neutron to atoms of the source material. As the material gets rid of the neutron, energy is released in the form of gamma rays. Two of the most common industrial gamma-ray sources for industrial radiography are Iridium-192 and Cobalt-60. In comparison to an X-ray generator, Cobalt-60 produces energies comparable to a *1.25 MV* X-ray system and Iridium-192 to a *460 kV* X-ray system. These high energies make it possible to penetrate thick materials with a relatively short exposure time. This and the fact that

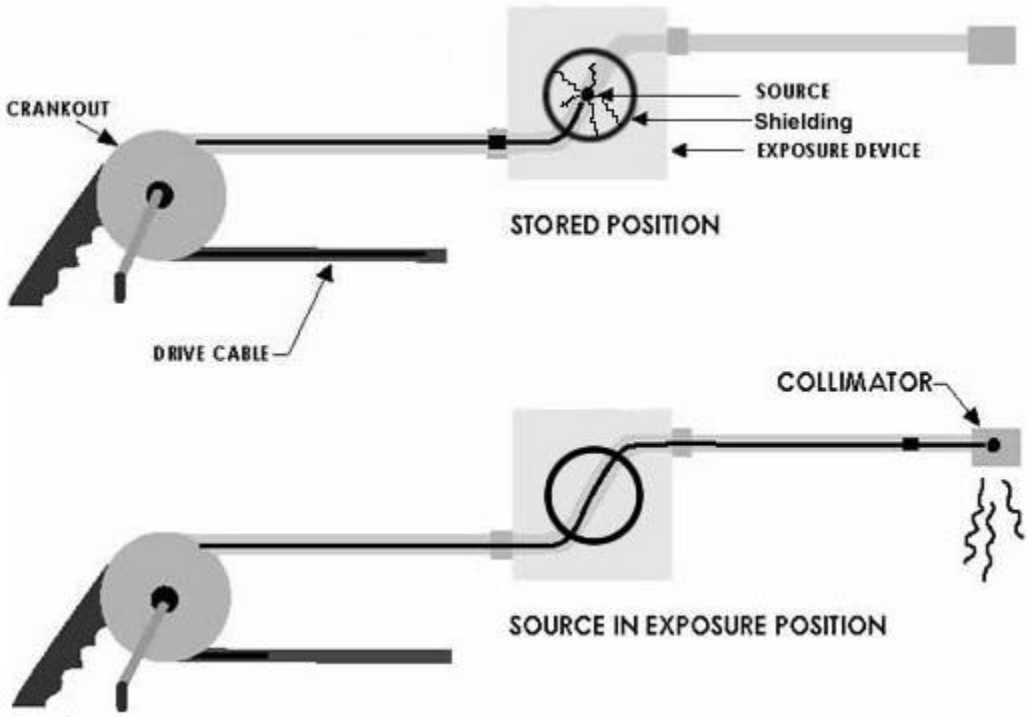
sources are very portable are the main reasons that gamma sources are widely used for field radiography. Of course, the disadvantage of a radioactive source is that it can never be turned off and safely managing the source is a constant responsibility.

Physical size of isotope materials varies between manufacturers, but generally an isotope material is a pellet that measures *1.5 mm* x *1.5 mm*. Depending on the level of activity desired, a pellet or pellets are loaded into a stainless steel capsule and sealed by welding. The capsule is attached to short flexible cable called a pigtail.


The source capsule and the pigtail are housed in a shielding device referred to as a exposure device or camera. Depleted uranium is often used as a shielding material for sources. The exposure device for Iridium-192 and Cobalt-60 sources will contain *22 kg* and *225 kg* of shielding materials, respectively. Cobalt cameras are often fixed to a trailer and transported to and from inspection sites. When the source is not being used to make an exposure, it is locked inside the exposure device.

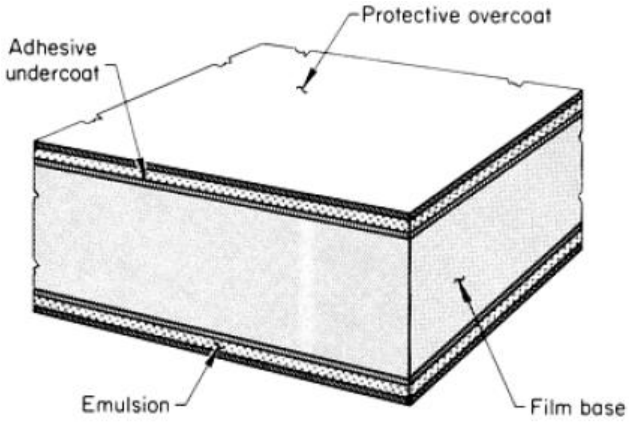



To make a radiographic exposure, a crank-out mechanism and a guide tube are attached to opposite ends of the exposure device. The guide tube often has a collimator (*usually made of tungsten*) at the end to shield the radiation except in the direction necessary to make the exposure. The end of the guide tube is secured in the location where the radiation source needs to be to produce the radiograph. The crank-out cable is stretched as far as possible to put as much distance as possible between the exposure device and the radiographer. To make the exposure, the radiographer quickly cranks the source out of the exposure device and into position in the collimator at the end of the guide tube. At the end of the exposure time, the source is cranked back into the exposure device. There is a series of safety procedures, which include several radiation surveys, that must be accomplished when making an exposure with a gamma source.




## Radiographic Film

X-ray films for general radiography basically consist of an emulsion-gelatin containing radiation-sensitive silver halide crystals (*such as silver bromide or silver chloride*). The emulsion is usually coated on both sides of a flexible, transparent, blue-tinted base in layers about *0.012 mm* thick. An adhesive undercoat fastens the emulsion to the film base and a very thin but tough coating covers the emulsion to protect it against minor abrasion. The typical total thickness of the X-ray film is approximately *0.23 mm*. Though films are made to be sensitive for X-ray or gamma-ray, yet they are also sensitive to visible light. When X-rays, gamma-rays, or light strike the film, some of the halogen atoms are liberated from the silver halide crystal and thus leaving the silver atoms alone. This change is of such a small nature that it cannot be detected by ordinary physical methods and is called a "*latent (hidden) image*". When the film is exposed to a chemical solution (*developer*) the reaction results in the formation of black, metallic silver.



### *Film Selection*

Selecting the proper film and developing the optimal radiographic technique for a particular component depends on a number of different factors;

- Composition, shape, and size of the part being examined and, in some cases, its weight and location.
- Type of radiation used, whether X-rays from an X-ray generator or gamma rays from a radioactive source.
- Kilovoltage available with the X-ray equipment or the intensity of the gamma radiation.
- Relative importance of high radiographic detail or quick and economical results.

### *Film Packaging*

Radiographic film can be purchased in a number of different packaging options and they are available in a variety of sizes. The most basic form is as individual sheets in a box. In preparation for use, each sheet must be loaded into a cassette or film holder in a darkroom to protect it from exposure to light.

Industrial X-ray films are also available in a form in which each sheet is enclosed in a light-tight envelope. The film can be exposed from either side without removing it from the protective packaging. A rip strip makes it easy to remove the film in the darkroom for processing.

Packaged film is also available in the form of rolls where that allows the radiographer to cut the film to any length. The ends of the packaging are sealed with electrical tape in the darkroom. In applications such as the radiography of circumferential welds and the examination of long joints on an aircraft fuselage, long lengths of film offer great economic advantage.

### *Film Handling*

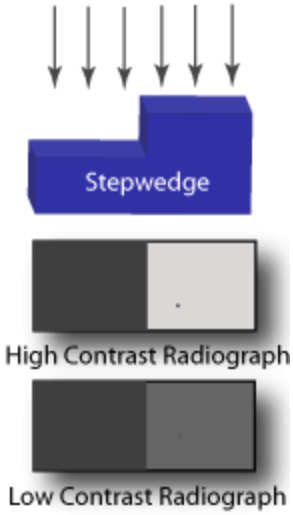
X-ray film should always be handled carefully to avoid physical strains, such as pressure, creasing, buckling, friction, etc. Whenever films are loaded in semi-flexible holders and external clamping devices are used, care should be taken to be sure pressure is uniform. Marks resulting from contact with fingers that are moist or contaminated with processing chemicals, as well as crimp marks, are avoided if large films are always grasped by the edges and allowed to hang free. Use of envelope-packed films avoids many of these problems until the envelope is opened for processing.

# ***RADIOGRAPHY CONSIDERATIONS & TECHNIQUES***

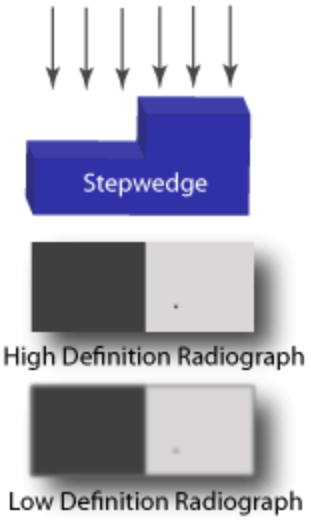
## Radiographic Sensitivity

The usual objective in radiography is to produce an image showing the highest amount of detail possible. This requires careful control of a number of different variables that can affect image quality. Radiographic sensitivity is a measure of the quality of an image in terms of the smallest detail or discontinuity that may be detected. Radiographic sensitivity is dependant on the contrast and the definition of the image.

*Radiographic contrast* is the degree of density (*darkness*) difference between two areas on a radiograph. Contrast makes it easier to distinguish features of interest, such as defects, from the surrounding area. The image to the right shows two radiographs of the same stepwedge. The upper radiograph has a high level of contrast and the lower radiograph has a lower level of contrast. While they are both imaging the same change in thickness, the high contrast image uses a larger change in radiographic density to show this change. In each of the two radiographs, there is a small dot, which is of equal density in both radiographs. It is much easier to see in the high contrast radiograph.




*Radiographic definition* is the abruptness of change in going from one area of a given radiographic density to another. Like contrast, definition also makes it easier to see features of interest, such as defects, but in a totally different way. In the image to the right, the upper radiograph has a high level of definition and the lower radiograph has a lower level of definition. In the high definition radiograph it can be seen that a change in the thickness of the stepwedge translates to an abrupt change in radiographic density. It can be seen that the details, particularly the small dot, are much easier to see in the high definition radiograph. It can be said that a faithful visual reproduction of the stepwedge was produced. In the lower image, the radiographic setup did not produce a faithful visual reproduction. The edge line between the steps is blurred. This is evidenced by the gradual transition between the high and low density areas on the radiograph.



## Radiographic "Image" Density

After taking a radiographic image of a part and processing the film, the resulting darkness of the film will vary according to the amount of radiation that has reached the film through the test object. As mentioned earlier, the darker areas indicate more exposure and lighter areas indicate less exposure. The processed film (*or image*) is usually viewed by placing it in front of a screen providing white light illumination of uniform intensity such that the light is transmitted through the film such that the image can be clearly seen. The term "radiographic density" is a measure of the degree of film darkening (*darkness of the image*). Technically it should be called "transmitted density" when associated with transparent-base film since it is a measure of the light transmitted through the film. Radiographic density is the logarithm of two measurements: the intensity of light incident on the film ($I_o$) and the intensity of light transmitted through the film ($I_t$). This ratio is the inverse of transmittance.

$$Density = \log \frac{I_o}{I_t}$$

Similar to the decibel, using the log of the ratio allows ratios of significantly different sizes to be described using easy to work with numbers. The following table shows numeric examples of the relationship between the amount of transmitted light and the calculated film density.

| **Transmittance** ($I_t/I_0$) | **Transmittance** (%) | **Inverse of Transmittance** ($I_0/I_t$) | **Density** ($Log(I_0/I_t)$) |
|---|---|---|---|
| 1.0 | 100% | 1 | 0 |
| 0.1 | 10% | 10 | 1 |
| 0.01 | 1% | 100 | 2 |
| 0.001 | 0.1% | 1000 | 3 |
| 0.0001 | 0.01% | 10000 | 4 |

From the table, it can be seen that a density reading of *2.0* is the result of only one percent of the incident light making it through the film. At a density of *4.0* only *0.01%* of transmitted light reaches the far side of the film. Industrial codes and standards typically require a radiograph to have a density between *2.0* and *4.0* for acceptable viewing with common film viewers. Above 4.0, extremely bright viewing lights is necessary for evaluation.

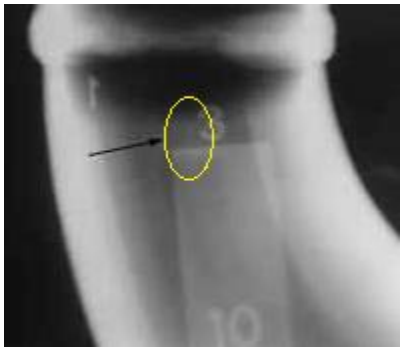
Film density is measured with a "*densitometer*" which simply measures the amount of light transmitted through a piece of film using a photovoltic sensor.

## Secondary (Scatter) Radiation Control

Secondary or scatter radiation must often be taken into consideration when producing a radiograph. The scattered photons create a loss of contrast and definition. Often, secondary radiation is thought of as radiation striking the film reflected from an object in the immediate area, such as a wall, or from the table or floor where the part is resting.

Control of side scatter can be achieved by moving objects in the room away from the film, moving the X-ray tube to the center of the vault, or placing a collimator at the exit port, thus reducing the diverging radiation surrounding the central beam.

When scarered radiation comes from objects behind the film, it is often called "backscatter". Industry codes and standards often require that a lead letter "*B*" be placed on the back of the cassette to verify the control of backscatter. If the letter "*B*" shows as a "*ghost*" image on the film, a significant amount of backscatter radiation is reaching the film. The image of the "*B*" is often very nondistinct as shown in the image to the right. The arrow points to the area of backscatter radiation from the lead "*B*" located on the back side of the film.



The control of backscatter radiation is achieved by backing the film in the cassette with a sheet of lead that is at least *0.25 mm* thick such that the sheet will be behind the film when it is exposed. It is a common practice in industry to place thin sheets of lead (*called "lead screens"*) in front and behind the film (*0.125 mm thick in front and 0.25 mm thick behind*).

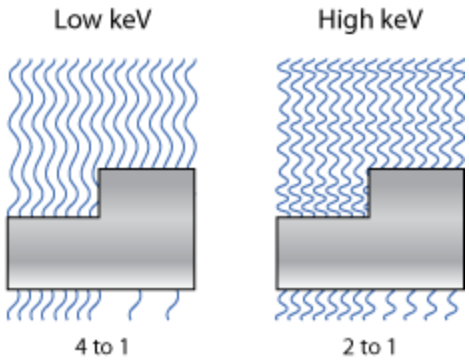
## Radiographic Contrast

As mentioned previously, radiographic contrast describes the differences in photographic density in a radiograph. The contrast between different parts of the image is what forms the image and the greater the contrast, the more visible features become. Radiographic contrast has two main contributors; subject contrast and film (*or detector*) contrast.

### *Subject Contrast*

Subject contrast is the ratio of radiation intensities transmitted through different areas of the component being evaluated. It is dependant on the absorption differences in the component, the wavelength of the primary radiation, and intensity and distribution of secondary radiation due to scattering.

It should be no surprise that absorption differences within the subject will affect the level of contrast in a radiograph. The larger the difference in thickness or density between two areas of the subject, the larger the difference in radiographic density or contrast. However, it is also possible to radiograph a particular subject and produce two radiographs having entirely different contrast levels. Generating X-rays using a low kilovoltage will generally result in a radiograph with high contrast. This occurs because low energy radiation is more easily attenuated. Therefore, the ratio of photons that are transmitted through a thick and thin area will be greater with low energy radiation.



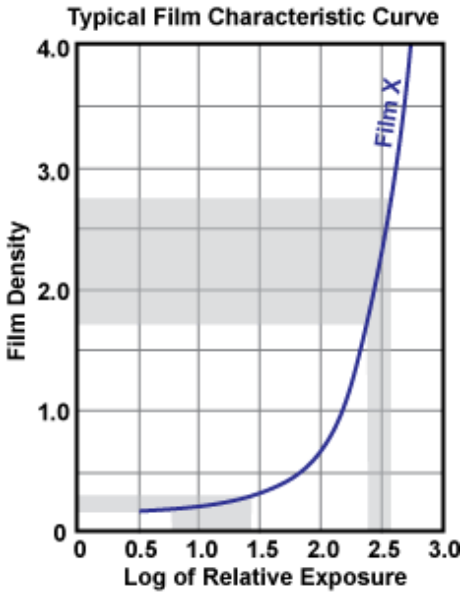

There is a tradeoff, however. Generally, as contrast sensitivity increases, the latitude of the radiograph decreases. Radiographic latitude refers to the range of material thickness that can be imaged. This means that more areas of different thicknesses will be visible in the image. Therefore, the goal is to balance radiographic contrast and latitude so that there is enough contrast to identify the features of interest but also to make sure the latitude is great enough so that all areas of interest can be inspected with one radiograph. In thick parts with a large range of thicknesses, multiple radiographs will likely be necessary to get the necessary density levels in all areas.

### *Film Contrast*

Film contrast refers to density differences that result due to the type of film being used, how it was exposed, and how it was processed. Since there are other detectors besides film, this could be called detector contrast, but the focus here will be on film. Exposing a film to produce higher film densities will generally increase the contrast in the radiograph.

A typical film characteristic curve, which shows how a film responds to different amounts of radiation exposure, is shown in the figure. From the shape of the curves, it can be seen that when the film has not seen many photon interactions (*which will*

*result in a low film density*) the slope of the curve is low. In this region of the curve, it takes a large change in exposure to produce a small change in film density. Therefore, the sensitivity of the film is relatively low. It can be seen that changing the log of the relative exposure from *0.75* to *1.4* only changes the film density from *0.20* to about *0.30*. However, at film densities above *2.0*, the slope of the characteristic curve for most films is at its maximum. In this region of the curve, a relatively small change in exposure will result in a relatively large change in film density. For example, changing the log of relative exposure from *2.4* to *2.6* would change the film density from *1.75* to *2.75*. Therefore, the sensitivity of the film is high in this region of the curve. In general, the highest overall film density that can be conveniently viewed or digitized will have the highest level of contrast and contain the most useful information.




As mentioned previously, thin lead sheets (*called "lead screens"*) are typically placed on both sides of the radiographic film during the exposure (*the film is placed between the lead screens and inserted inside the cassette*). Lead screens in the thickness range of *0.1 to 0.4 mm* typically reduce the scattered radiation at energy levels below *150 kV*. Above this energy level, they will emit electrons to provide more exposure of the film, thus increasing the density and contrast of the radiograph.

Other type of screens called "fluorescent screens" can alternatively be used where they produce visible light when exposed to radiation and this light further exposes the film and increases density and contrast.

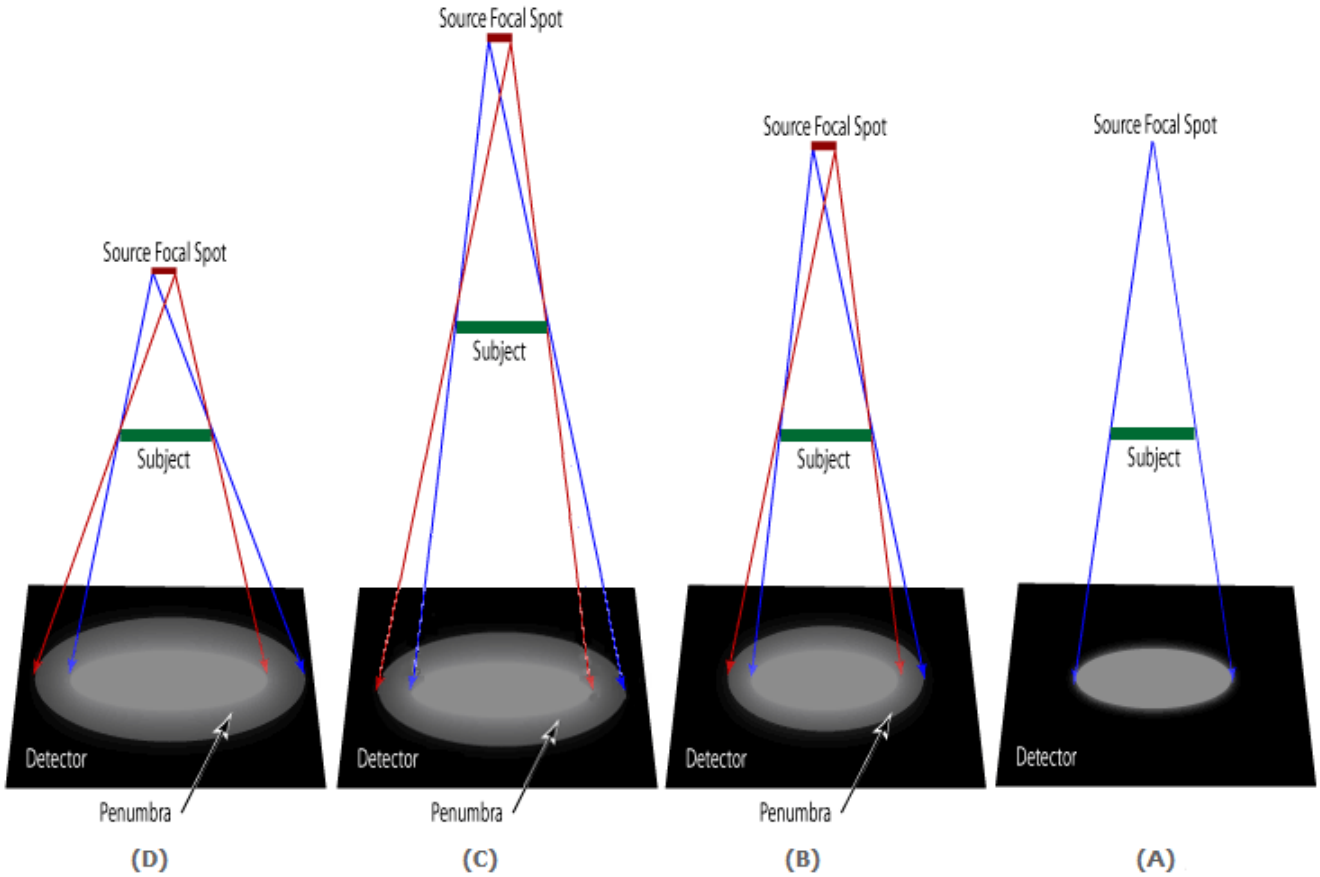
## Radiographic Definition

As mentioned previously, radiographic definition is the abruptness of change from one density to another. Both geometric factors of the equipment and the radiographic setup, and film and screen factors have an effect on definition.

### *Geometric Factors*

The loss of definition resulting from geometric factors of the radiographic equipment and setup is refered to as "*geometric unsharpness*". It occurs because the radiation

does not originate from a single point but rather over an area. The three factors controlling unsharpness are source size, source to object distance, and object to detector (film) distance. The effects of these three factors on image defenetion is illustrated by the images below (*source size effect; compare **A** & **B**, source to object distance; compare **B** & **D**, and object to detector distance; compare **B** & **C***).




The source size is obtained by referencing manufacturers specifications for a given X-ray or gamma ray source. Industrial X-ray tubes often have focal spot sizes of *1.5 mm* squared but microfocus systems have spot sizes in the *30 micron* range. As the source size decreases, the geometric unsharpness also decreases. For a given size source, the unsharpness can also be decreased by increasing the source to object distance, but this comes with a reduction in radiation intensity. The object to detector distance is usually kept as small as possible to help minimize unsharpness. However, there are situations, such as when using geometric enlargement, when the object is separated from the detector, which will reduce the definition.

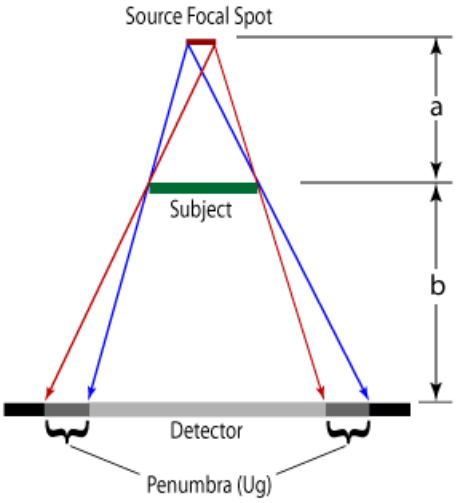
In general, in order to produce the highest level of definition, the focal-spot or source size should be as close to a point source as possible, the source-to-object distance

should be as large as practical, and the object-to-detector distance should be a small as practical.

Codes and standards used in industrial radiography require that geometric unsharpness be limited. In general, the allowable amount is *1/100* of the material thickness up to a maximum of *1 mm*. These values refer to the width of penumbra shadow in a radiographic image.

The amount of geometric unsharpness ($U_g$) can be calculated using the following geometric formula:

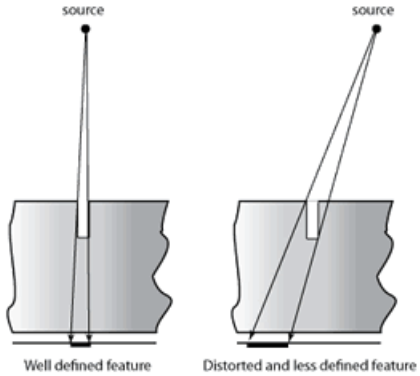
$$U_g = d_s \frac{b}{a}$$




Where;

- $d_s$ : source focal-spot size
- $a$ : distance from the source to the front surface of the object
- $b$ : distance from the front surface of the object to the detector (*or the thickness of the object if a thick object is placed immediately on top of the detector*)

The angle between the radiation and some features will also have an effect on definition. If the radiation is parallel to an edge or linear discontinuity, a sharp distinct boundary will be seen in the image. However, if the radiation is not parallel with the discontinuity, the feature will appear distorted, out of position and less defined in the image.




Abrupt changes in thickness and/or density will appear more defined in a radiograph than will areas of gradual change. For example, consider a circle. Its largest dimension will be a cord that passes through its centerline. As the cord is moved away from the centerline, the thickness gradually decreases. It is sometimes difficult to locate the edge of a void due to this gradual change in thickness.

Lastly, any movement of the specimen, source or detector during the exposure will reduce definition. Similar to photography, any movement will result in blurring of the image. Vibration from nearby equipment may be an issue in some inspection situations.

### *Film and Screen Factors*

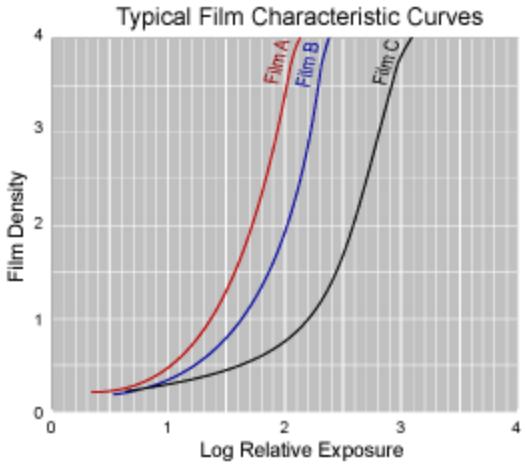
The last set of factors concern the film and the use of fluorescent screens. A fine grain film is capable of producing an image with a higher level of definition than is a coarse grain film. Wavelength of the radiation will influence apparent graininess. As the wavelength shortens and penetration increases, the apparent graininess of the film will increase. Also, increased development of the film will increase the apparent graininess of the radiograph.

The use of fluorescent screens also results in lower definition. This occurs for a couple of different reasons. The reason that fluorescent screens are sometimes used is because incident radiation causes them to give off light that helps to expose the film. However, the light they produce spreads in all directions, exposing the film in adjacent areas, as well as in the areas which are in direct contact with the incident radiation. Fluorescent screens also produce screen mottle on radiographs. Screen mottle is associated with the statistical variation in the numbers of photons that interact with the screen from one area to the next.

## Film Characteristic Curves

In film radiography, the number of photons reaching the film determines how dense the film will become when other factors such as the developing time are held constant. The number of photons reaching the film is a function of the intensity of the radiation and the time that the film is exposed to the radiation. The term used to describe the control of the number of photons reaching the film is “exposure”.

Different types of radiographic films respond differently to a given amount of exposure. Film manufacturers commonly characterize their film to determine the relationship between the applied exposure and the resulting film density. This relationship commonly varies over a range of film densities, so the data is presented in the form of a curve such as the one for *Kodak AA400* shown to the right. This plot is usually called a film characteristic curve or density curve. A log scale is sometimes used for the *x*-axis or it is more common that the values are reported in log units on a linear scale as seen in the figure. Also, relative exposure values (*unitless*) are often used. Relative exposure is the ratio of two exposures. For



example, if one film is exposed at *100 kV* for *6 mA.min* and a second film is exposed at the same energy for *3 mA.min*, then the relative exposure would be *2*.

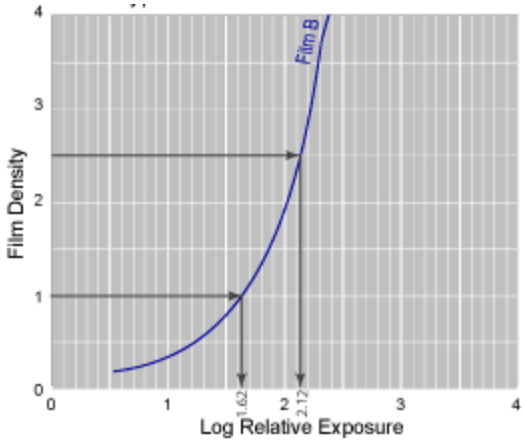
The location of the characteristic curves of different films along the *x*-axis relates to the speed of the film. The farther to the right that a curve is on the chart, the slower the film speed (*Film A has the highest speed while film C has the lowest speed*). The shape of the characteristic curve is largely independent of the wavelength of the X-ray or gamma ray, but the location of the curve along the *x*-axis, with respect to the curve of another film, does depend on radiation quality.

Film characteristic curves can be used to adjust the exposure used to produce a radiograph with a certain density to an exposure that will produce a second radiograph of higher or lower film density. The curves can also be used to relate the exposure produced with one type of film to exposure needed to produce a radiograph of the same density with a second type of film.

***Example 1:*** *Adjusting the Exposure to Produce a Different Film Density*

> A type *B* Film was exposed with *140 kV* at *1 mA* for *10 seconds* (*i.e., 10 mA.s*) and the resulting radiograph had a density of *1.0*. If the desired density is 2.5, what should be the exposure?

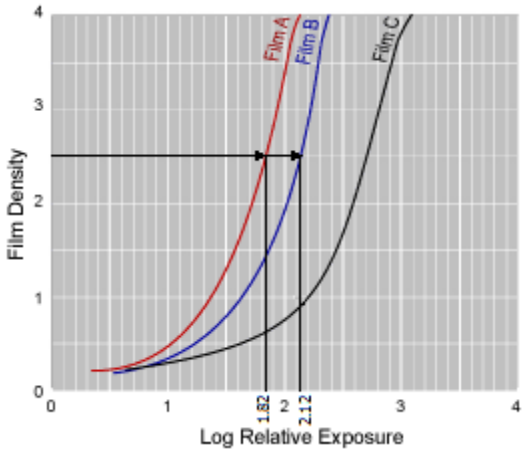
From the graph, the log of the relative exposure of a density of *1.0* is *1.62* and the log of the relative exposure when the density of the film is *2.5* is *2.12*.
The difference between the two values is *0.5*.
$10^{0.5} = 3.16$
Therefore, the exposure used to produce the initial radiograph with a *1.0* density needs to be multiplied by *3.16* to produce a radiograph with the desired density of *2.5*.
So the new exposure must be:
*10 mA.s* x *3.16* = *31.6 mA.s* (at *140 kV*)




***Example 2:*** *Adjusting the Exposure to Allow Use of a Different Film Type*

> Suppose an acceptable radiograph with a density of *2.5* was produced by exposing *Film A* for *30 seconds* at *1mA* and *130 kV*. What should be the exposure if we want to produce the same density using *Film B*?

From the graph, the log of the relative exposure that produced a density of *2.5* on *Film A* is *1.82* and the log of the relative exposure that produces the same density on *Film B* is *2.12*.
The difference between the two values is *0.3*.
$10^{0.3} = 2$
So the exposure for *Film B* must be:
*30 mA.s* x *2* = *60 mA.s* (at *130 kV*)




## Exposure Calculations

Properly exposing a radiograph is often a trial and error process, as there are many variables that affect the final radiograph. Some of the variables that affect the density of the radiograph include:

- The spectrum of radiation produced by the X-ray generator.
- The voltage potential used to generate the X-rays (*kV*).
- The amperage used to generate the X-rays (*mA*).
- The exposure time.
- The distance between the radiation source and the film.
- The material of the component being radiographed.
- The thickness of the material that the radiation must travel through.
- The amount of scattered radiation reaching the film.
- The film being used.
- The use of lead screens or fluorescent screens.
- The concentration of the film processing chemicals and the contact time.

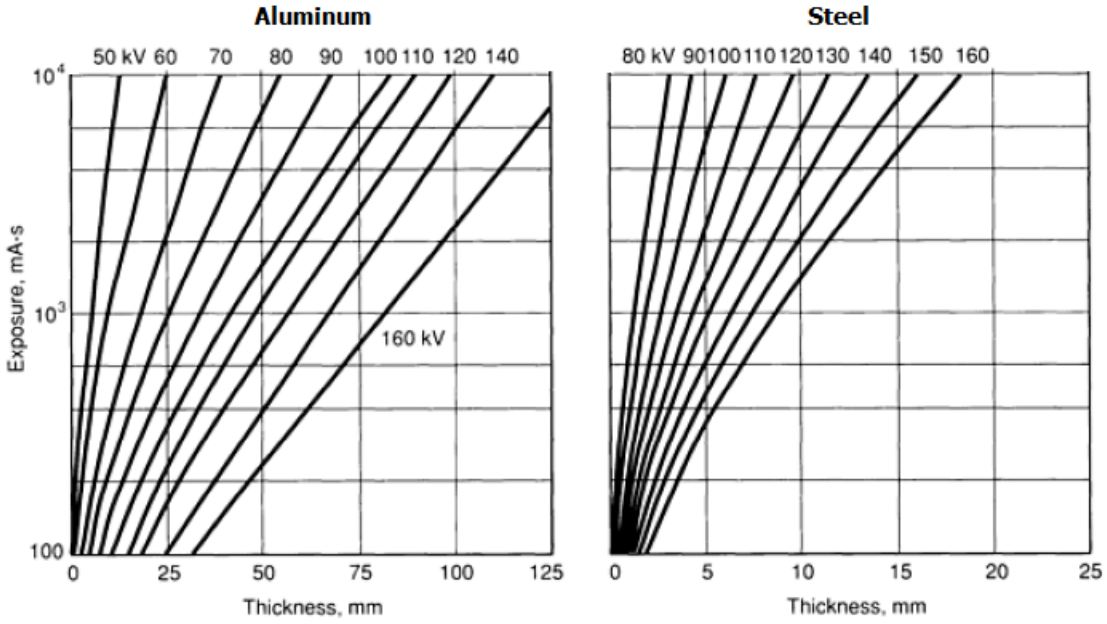
The current industrial practice is to develop a procedure that produces an acceptable density by trail for each specific X-ray generator. This process may begin using published exposure charts to determine a starting exposure, which usually requires some refinement.

However, it is possible to calculate the density of a radiograph to an acceptable degree of accuracy when the spectrum of an X-ray generator has been characterized. The calculation cannot completely account for scattering but, otherwise, the relationship between many of the variables and their effect on film density is known. Therefore, the change in film density can be estimated for any given variable change. For example, from Newton's Inverse Square Law, it is known that the intensity of the radiation varies inversely with the square of the distance from the source. It is also

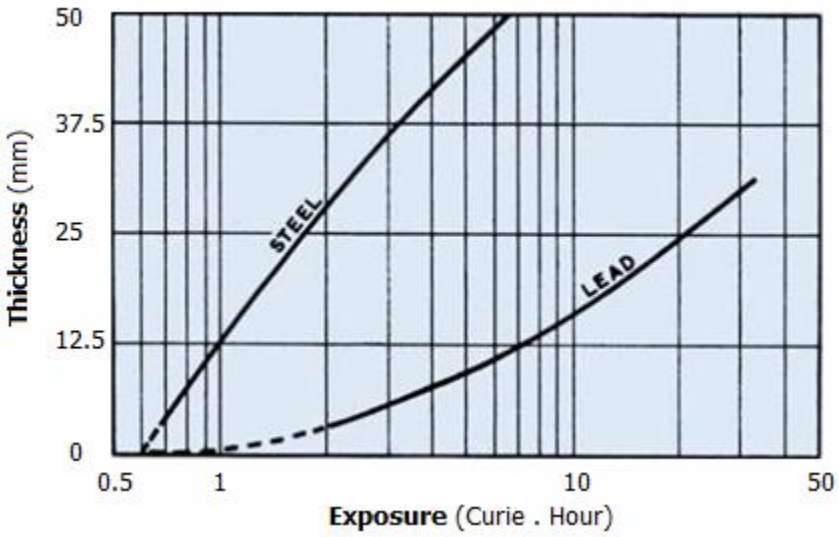
known that the intensity of the radiation transmitted through a material varies exponentially with the linear attenuation coefficient and the thickness of the material. By calculating the intensity from these equations one can directly calculate the required exposure knowing that the exposure is inversely related to the intensity as:

$$Intensity_1 \times Exposure_1 = Intensity_2 \times Exposure_2$$

The figure below shows exemplary exposure charts for two materials for a specific X-ray generator for the flowing parameters: film density of *2.0* without screens, *910 mm* source-to-film distance, *Industrex AA* film & *7* minutes development time.




For gamma-ray sources, however, the required exposure can be more easily calculated since the radiation spectrum is well known for each different radiation source. The exposure is usually expressed in Curie-Time units and the data can be represented in the form of chars or in tabulated form. The figure shows a typical exposure chart for *Ir-192* at the following parameters: film density of *1.75* without screens, *455 mm* source-to-film distance, *II-ford* film & *6* minutes development time.



It should be noted that such charts are valid for the specified parameters, but of course using the data in the charts one can calculate the exposure for different set of parameters such as different source-to-film distance, different type of film, or different density.

***Example 1:***

A *25 mm* thick Aluminum plate is to be radiographed on *type C film* without screens using X-ray generator at *80 kV* and *500 mm* distance. What is the minimum required exposure time to get *3.0* density (*for same development parameters as used for the chart, and considering the film used for the chart to be type A*) knowing that the max current setting for the X-ray machine is *20 mA*?

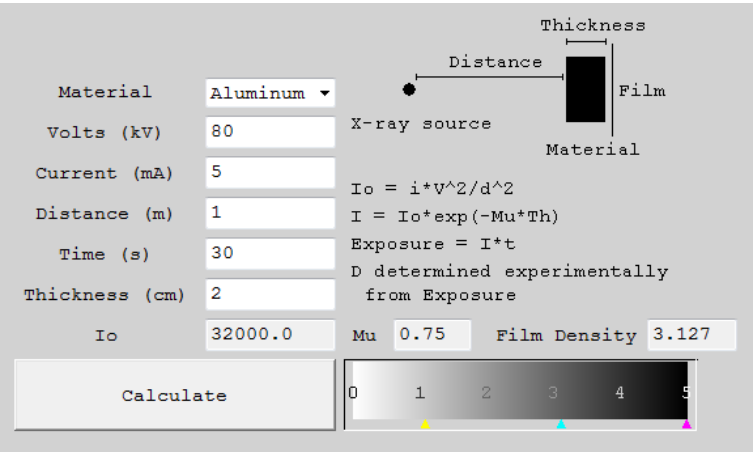
***Answer:*** *190 s*

***Example 2:***

A *12.5 mm* thick Steel plate is to be radiographed without screens using Ir-192 source at 45*5 mm* distance. Knowing that the source activity was *100 Ci* before *30 days*, what is the required exposure time (*for same density, film type, and development parameters as used for the chart*) if the plate is to be place behind a *50 mm* thick concrete wall while it is being exposed?

***Answer:*** *104 s*

To make such calculations more easy, radiographic modeling calculators and programs can be used. A number of such programs are available from different sources and some are available online. These programs can provide a fair representation of the radiograph that will be produced with a specific setup and parameters. The figure shows a screen shot of an online calculator available at the (*www.ndt-ed.org*) website.



## Controlling Radiographic Quality

One of the methods of controlling the quality of a radiograph is through the use of image quality indicators (IQIs), which are also referred to as *penetrameters*. IQIs provide means of visually informing the film interpreter of the contrast sensitivity and definition of the radiograph. The IQI indicates that a specified amount of change in material thickness will be detectable in the radiograph, and that the radiograph has a certain level of definition so that the density changes are not lost due to unsharpness. Without such a reference point, consistency and quality could not be maintained and defects could go undetected.

IQIs should be placed on the source side of the part over a section with a material thickness equivalent to the region of interest. If this is not possible, the IQI may be placed on a block of similar material and thickness to the region of interest. When a block is used, the IQI should be the same distance from the film as it would be if placed directly on the part in the region of interest. The IQI should also be placed slightly away from the edge of the part so that at least three of its edges are visible in the radiograph.

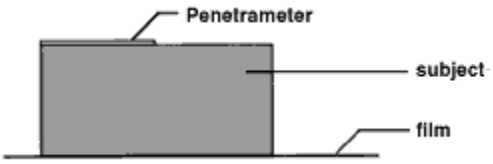
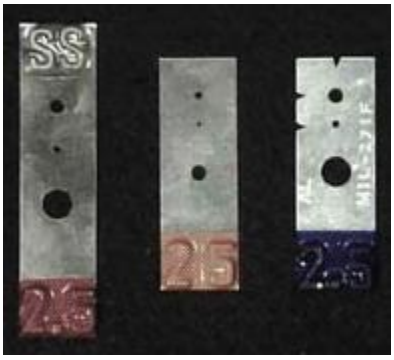



Image quality indicators take many shapes and forms due to the various codes or standards that invoke their use. The two most commonly used IQI types are: the hole-type and the wire IQIs. IQIs come in a variety of material types so that one with radiation absorption characteristics similar to the material being radiographed can be used.

### *Hole-Type IQIs*

ASTM Standard E1025 gives detailed requirements for the design and material group classification of hole-type image quality indicators. Hole-type IQIs are classified in eight groups based on their radiation absorption characteristics. A notching system is used to indicate the IQI material. The numbers on the IQI indicate the sample thickness that the IQI would typically be placed on. Also, holes of different sizes are present where these holes should be visible on the radiograph. It should be noted however that the IQI is used to indicate the quality of the radiographic technique and not intended to be used as a measure of the size of a cavity that can be located on the radiograph.



***Wire IQIs***


ASTM Standard E747 covers the radiographic examination of materials using wire IQIs to control image quality. Wire IQIs consist of a set of six wires arranged in order of increasing diameter and encapsulated between two sheets of clear plastic. Wire IQIs are grouped in four sets each having different range of wire diameters. The set letter (***A***, ***B***, ***C*** or ***D***) is shown in the lower right corner of the IQI. The number in the lower left corner indicates the material group.

## Film Processing

As mentioned previously, radiographic film consists of a transparent, blue-tinted base coated on both sides with an emulsion. The emulsion consists of gelatin containing microscopic, radiation sensitive silver halide crystals, such as silver bromide and silver chloride. When X-rays, gamma rays or light rays strike the crystals or grains, some of the *Br-* ions are liberated leaving the *Ag+* ions. In this condition, the radiograph is said to contain a latent (hidden) image because the change in the grains is virtually undetectable, but the exposed grains are now more sensitive to reaction with the developer.

When the film is processed, it is exposed to several different chemical solutions for controlled periods of time. Film processing basically involves the following five steps:

*Development*: The developing agent gives up electrons to convert the silver halide grains to metallic silver. Grains that have been exposed to the radiation develop more rapidly, but given enough time the developer will convert all the silver ions into silver metal. Proper temperature control is needed to convert exposed grains to pure silver while keeping unexposed grains as silver halide crystals.

*Stopping the development*: The stop bath simply stops the development process by diluting and washing the developer away with water.

*Fixing*: Unexposed silver halide crystals are removed by the fixing bath. The fixer dissolves only silver halide crystals, leaving the silver metal behind.

*Washing*: The film is washed with water to remove all the processing chemicals.

*Drying*: The film is dried for viewing.

Film processing is a strict science governed by rigid rules of chemical concentration, temperature, time, and physical movement. Whether processing is done by hand or automatically by machine, excellent radiographs require a high degree of consistency and quality control.

## Viewing Radiographs

After the film processing, radiographs are viewed using a light-box (*or they can be digitized and viewed on a high resolution monitor*) in order to be interpreted. In addition to providing diffused, adjustable white illumination of uniform intensity, specialized industrial radiography light-boxes include magnifying and masking aids. When handing the radiographs, thin cotton gloves should be worn to prevent fingerprints on the radiographs.

# ***RADIATION SAFETY***

## Radiation Health Risks

As mentioned previously, the health risks associated with the radiation is considered to be one the major disadvantages of radiogaphy. The amount of risk depends on the amount of radiation dose received, the time over which the dose is received, and the body parts exposed. The fact that X-ray and gamma-ray radiation are not detectable by the human senses complicates matters further. However, the risks can be minimized and controlled when the radiation is handled and managed properly in accordance to the radiation safety rules. The active laws all over the world require that individuals working in the field of radiography receive training on the safe handling and use of radioactive materials and radiation producing devices.

Today, it can be said that radiation ranks among the most thoroughly investigated (and somehow understood) causes of disease. The primary risk from occupational radiation exposure is an increased risk of cancer. Although scientists assume low-level radiation exposure increases one's risk of cancer, medical studies have not demonstrated adverse health effects in individuals exposed to small chronic radiation doses.

The occurrence of particular health effects from exposure to ionizing radiation is a complicated function of numerous factors including:

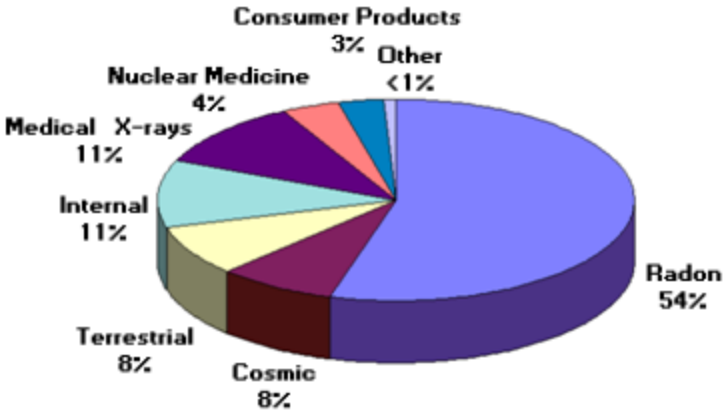
- *Type of radiation involved*. All kinds of ionizing radiation can produce health effects. The main difference in the ability of alpha and beta particles and gamma and X-rays to cause health effects is the amount of energy they have. Their energy determines how far they can penetrate into tissue and how much energy they are able to transmit directly or indirectly to tissues.
- *Size of dose received*. The higher the dose of radiation received, the higher the likelihood of health effects.
- *Rate at which the dose is received*. Tissue can receive larger dosages over a period of time. If the dosage occurs over a number of days or weeks, the results are often not as serious if a similar dose was received in a matter of minutes.
- *Part of the body exposed*. Extremities such as the hands or feet are able to receive a greater amount of radiation with less resulting damage than blood forming organs housed in the upper body.
- *The age of the individual*. As a person ages, cell division slows and the body is less sensitive to the effects of ionizing radiation. Once cell division has slowed, the

effects of radiation are somewhat less damaging than when cells were rapidly dividing.

- *Biological differences*. Some individuals are more sensitive to radiation than others. Studies have not been able to conclusively determine the cause of such differences.

## Sources of High Energy Radiation

There are many sources of harmful, high energy radiation. Industrial radiographers are mainly concerned with exposure from X-ray generators and radioactive isotopes. However, it is important to understand that eighty percent of human exposure comes from natural sources such as radon gas, outer space, rocks and soil, and the human body. The remaining twenty percent comes from man-made radiation sources, such as those used in medical and dental diagnostic procedures.




One source of natural radiation is cosmic radiation. The earth and all living things on it are constantly being bombarded by radiation from space. The sun and stars emit electromagnetic radiation of all wavelengths. The dose from cosmic radiation varies in different parts of the world due to differences in elevation and the effects of the earth's magnetic field. Radioactive materials are also found throughout nature where they occur naturally in soil, water, plants and animals. The major isotopes of concern for terrestrial radiation are uranium and the decay products of uranium, such as thorium, radium, and radon. Low levels of uranium, thorium, and their decay products are found everywhere. Some of these materials are ingested with food and water, while others, such as radon, are inhaled. The dose from terrestrial sources varies in different parts of the world. Locations with higher concentrations of uranium and thorium in their soil have higher dose levels. All people also have radioactive isotopes, such as potassium-40 and carbon-14, inside their bodies. The variation in dose from one person to another is not as great as the variation in dose from cosmic and terrestrial sources.

There are also a number of manmade radiation sources that present some exposure to the public. Some of these sources include tobacco, television sets, smoke detectors, combustible fuels, certain building materials, nuclear fuel for energy production, nuclear weapons, medical and dental X-rays, nuclear medicine, X-ray security systems

and industrial radiography. By far, the most significant source of man-made radiation exposure to the average person is from medical procedures, such as diagnostic X-rays, nuclear medicine, and radiation therapy.

## Measures Relative to the Biological Effects of Radiation Exposure

There are four measures of radiation that radiographers will commonly encounter when addressing the biological effects of working with X-rays or gamma-rays. These measures are: Exposure, Dose, Dose Equivalent, and Dose Rate. A short description of these measures and their units is given below

***Exposure*:** Exposure is a measure of the strength of a radiation field at some point in air (*the amount of charge produced in a unit mass of air when the interacting photons are completely absorbed in that mass*). This is the measure made by radiation survey meters since it can be easily and directly measured. The most commonly used unit of exposure is the "*roentgen*" (***R***).

***Dose or Absorbed Dose*:** While *exposure* is defined for air, the *absorbed dose* is the amount of energy that ionizing radiation imparts to a given mass of matter. In other words, the dose is the amount of radiation absorbed by and object. The *SI* unit for absorbed dose is the "*gray*" (***Gy***), but the "***rad***" (*Radiation Absorbed Dose*) is commonly used (*1* ***Gy*** *= 100* ***rad***). Different materials that receive the same exposure may not absorb the same amount of radiation. In human tissue, one ***Roentgen*** of X-ray or gamma radiation exposure results in about one ***rad*** of absorbed dose. The size of the absorbed dose is dependent upon the intensity (or activity) of the radiation source, the distance from the source, and the time of exposure to radiation.

***Dose Equivalent*:** The dose equivalent relates the absorbed dose to the biological effect of that dose. The absorbed dose of specific types of radiation is multiplied by a "*quality factor*" to arrive at the dose equivalent. The *SI* unit is the "*Sievert*" (***Sv***), but the "***rem***" (*Roentgen Equivalent in Man*) is commonly used (*1* ***Sv*** *= 100* ***rem***). The table below presents the "*Q* factors" for several types of radiation.

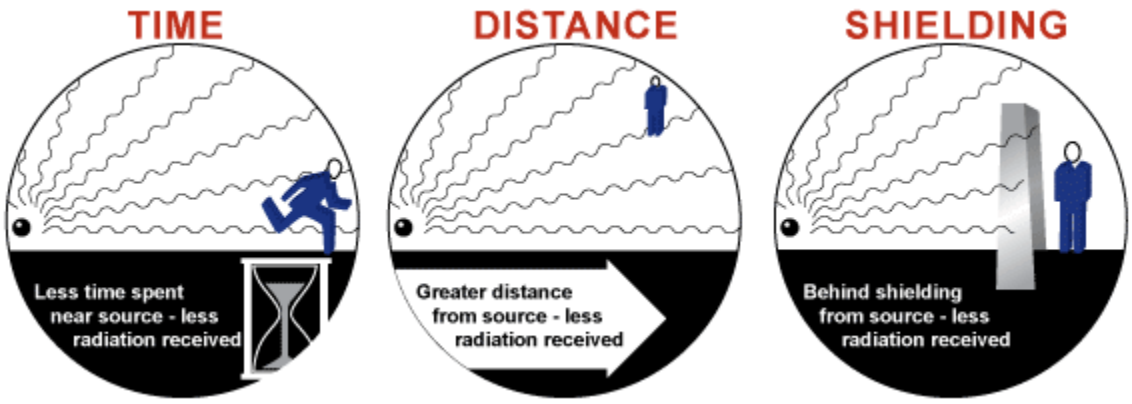
| Type of Radiation | Rad | Q Factor | Rem |
|---|---|---|---|
| *X-Ray* | 1 | 1 | 1 |
| *Gamma Ray* | 1 | 1 | 1 |
| *Beta Particles* | 1 | 1 | 1 |
| *Thermal Neutrons* | 1 | 5 | 5 |
| *Fast Neutrons* | 1 | 10 | 10 |
| *Alpha Particles* | 1 | 20 | 20 |

***Dose Rate*:** The dose rate is a measure of how fast a radiation dose is being received. Dose rate is usually presented in terms of *mR/hr, mrem/hr, rad/min, mGy/sec*, etc. Knowing the dose rate, allows the dose to be calculated for a period of time.

## Controlling Radiation Exposure

When working with radiation, there is a concern for two types of exposure: acute and chronic. An acute exposure is a single accidental exposure to a high dose of radiation during a short period of time. An acute exposure has the potential for producing both non-stochastic and stochastic effects. Chronic exposure, which is also sometimes called "continuous exposure", is long-term, low level overexposure. Chronic exposure may result in stochastic health effects and is likely to be the result of improper or inadequate protective measures.

The three basic ways of controlling exposure to harmful radiation are: ***1***) limiting the time spent near a source of radiation, ***2***) increasing the distance away from the source, ***3***) and using shielding to stop or reduce the level of radiation.




***Time***

The radiation dose is directly proportional to the time spent in the radiation. Therefore, a person should not stay near a source of radiation any longer than necessary. If a survey meter reads *4 mR/h* at a particular location, a total dose of *4 mR* will be received if a person remains at that location for one hour. The received dose can be simply calculated as: *Dose = Dose Rate x Time*

When using a gamma camera, it is important to get the source from the shielded camera to the collimator (*a device that shields radiation in some directions but allow it pass in one or more other directions*) as quickly as possible to limit the time of exposure to the unshielded source.

### *Distance*

Increasing distance from the source of radiation will reduce the amount of radiation received. As radiation travels from the source, it spreads out becoming less intense. This phenomenon can be expressed by the *Newton inverse square law*, which states that as the radiation travels out from the source, the dosage decreases inversely with the square of the distance: $I_1 / I_2 = D_2^2 / D_1^2$

### *Shielding*


The third way to reduce exposure to radiation is to place something between the radiographer and the source of radiation. In general, the more dense the material the more shielding it will provide. Lead and concrete are the most commonly used radiation shielding materials primarily because they are easy to work with and are readily available materials. Concrete is commonly used in the construction of radiation vaults. Some vaults will also be lined with lead sheeting to help reduce the radiation to acceptable levels on the outside.

## Exposure Limits

Over the years, numerous recommendations regarding occupational exposure limits have been developed by international radiation safety commissions. In general, the guidelines established for radiation exposure have had two principal objectives: ***1***) to prevent acute exposure; and ***2***) to limit chronic exposure to "acceptable" levels.

Current guidelines are based on the conservative assumption that there is no safe level of exposure. This assumption has led to the general philosophy of not only keeping exposures below recommended levels or regulation limits but also maintaining all exposure "***as low as reasonably achievable***" (*ALARA*). ALARA is a basic requirement of current radiation safety practices. It means that every reasonable effort must be made to keep the dose to workers and the public as far below the required limits as possible.

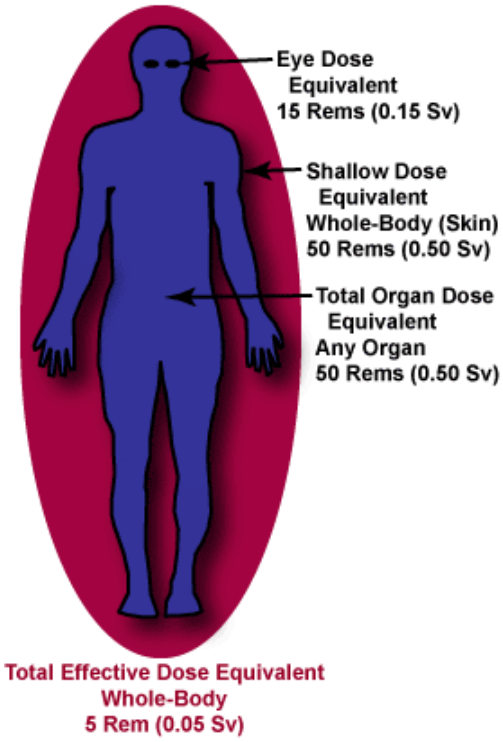
In general, most international radiation safety codes specify that the dose rate must not exceed *2mR/hour* in any unrestricted area. The specifications for the accumulated dose per year differ between radiation workers and non-workers. The limits are as follows:

### *Regulatory Limits for Occupational Exposure*

Most international codes set the annual limit of exposure for industrial radiographers who generally are not concerned with an intake of radioactive material as follows:

1) the more limiting of:
   - A total effective dose equivalent of *5 rem* (*0.05 Sv*)
     ***or***
   - The sum of the deep-dose equivalent to any individual organ or tissue other than the lens of the eye being equal to *50 rem* (*0.5 Sv*).

2) The annual limits to the lens of the eye, to the skin, and to the extremities, which are:
   - A lens dose equivalent of *15 rem* (*0.15 Sv*)
   - A shallow-dose equivalent of *50 rem* (*0.50 Sv*) to the skin or to any extremity.




The *shallow-dose equivalent* is the external dose to the skin of the whole-body or extremities from an external source of ionizing radiation. This value is the dose equivalent at a tissue depth of *0.007 cm* averaged over an area of *10 $cm^2$*.

The *lens dose equivalent* is the dose equivalent to the lens of the eye from an external source of ionizing radiation. This value is the dose equivalent at a tissue depth of *0.3 cm*.

The *deep-dose equivalent* is the whole-body dose from an external source of ionizing radiation. This value is the dose equivalent at a tissue depth of *1 cm*.

The *total effective dose equivalent* is the dose equivalent to the whole-body.

### *Declared Pregnant Workers and Minors*

Because of the increased health risks to the rapidly developing embryo and fetus, pregnant women can receive no more than *0.5 rem* during the entire gestation period

(*this is 10% of the dose limit that normally applies to radiation workers*). The same limit also applies to persons under the age of 18 years.

### *Non-radiation Workers and the General Public*

The dose limit to non-radiation workers and members of the public is only *2%* of the annual occupational dose limit. Therefore, a non-radiation worker can receive a whole body dose of no more that *0.1 rem/year* from industrial ionizing radiation. This exposure would be in addition to the *0.3 rem/year* from natural background radiation and the *0.05 rem/year* from man-made sources such as medical X-rays.

## Over-Dose Health Symptoms

Listed below are some of the probable prompt and delayed effects of certain doses of radiation when the doses are received by an individual within a twenty-four hour period.

- *0-25 rem* No injury evident. First detectable blood change at *5 rem*.
- *25-50 rem* Definite blood change at *25 rem*. No serious injury.
- *50-100 rem* Some injury possible.
- *100-200 rem* Injury and possible disability.
- *200-400 rem* Injury and disability likely, death possible.
- *400-500 rem* Median Lethal Dose (MLD) 50% of exposures are fatal.
- *500-1,000 rem* Up to 100% of exposures are fatal.
- *Over 1,000 rem* 100% likely fatal.

The delayed effects of radiation may be due either to a single large overexposure or continuing low-level overexposure.

Example dosages and resulting symptoms when an individual receives an exposure to the whole body within a twenty-four hour period.

*100 - 200 rem*

| | |
|---|---|
| *First Day* | No definite symptoms |
| *First Week* | No definite symptoms |
| *Second Week* | No definite symptoms |

| | |
|---|---|
| *Third Week* | Loss of appetite, malaise, sore throat and diarrhea |
| *Fourth Week* | Recovery is likely in a few months unless complications develop because of poor health |

*400 - 500 rem*

| | |
|---|---|
| *First Day* | Nausea, vomiting and diarrhea, usually in the first few hours |
| *First Week* | Symptoms may continue |
| *Second Week* | Epilation, loss of appetite |
| *Third Week* | Hemorrhage, nosebleeds, inflammation of mouth and throat, diarrhea, emaciation |
| *Fourth Week* | Rapid emaciation and mortality rate around 50% |

## Radiation Detectors

Instruments used for radiation measurement fall into two broad categories:

- Rate measuring instruments.
- Personal dose measuring instruments.

Rate measuring instruments measure the rate at which exposure is received (*more commonly called the radiation intensity*). Survey meters, audible alarms and area monitors fall into this category. These instruments present a radiation intensity reading relative to time, such as *R/hr* or *mR/hr*. An analogy can be made between these instruments and the speedometer of a car because both are measuring units relative to time.

Dose measuring instruments are those that measure the total amount of exposure received during a measuring period. The dose measuring instruments, or dosimeters, that are commonly used in industrial radiography are small devices which are designed to be worn by an individual to measure the exposure received by the individual. An analogy can be made between these instruments and the odometer of a car because both are measuring accumulated units.

### *Survey Meters*

The survey meter is the most important resource a radiographer has to determine the presence and intensity of radiation. There are many different models of survey meters available to measure radiation in the field. They all basically consist of a detector and a readout display. Analog and digital displays are available. Most of the survey meters used for industrial radiography use a gas filled detector.

Gas filled detectors consists of a gas filled cylinder with two electrodes having a voltage applied to them. Whenever the device is brought near radioactive substances, the gas becomes ionized. The electric field created by the potential difference between the anode and cathode causes the electrons of each ion pair to move to the anode while the positively charged gas atom is drawn to the cathode. This results in an electrical signal that is amplified, correlated to exposure and displayed as a value.

### *Audible Alarm Rate Meters*


Audible alarms are devices that emit a short "beep" or "chirp" when a predetermined exposure has been received. It is required that these electronic devices be worn by an individual working with gamma emitters. These devices reduce the likelihood of accidental exposures in industrial radiography by alerting the radiographer to exposure levels or dosages of radiation above a preset amount. It is important to note that audible alarms are not intended to be and should not be used as replacements for survey meters. Modern survey meters have this alarm feature already built in.

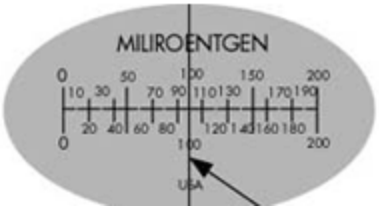
### *Pocket Dosimeter*

Pocket dosimeters are used to provide the wearer with an immediate reading of his or her exposure to X-rays or gamma rays. As the name implies, they are commonly worn in the pocket. The principal advantage of a pocket dosimeter is its ability to provide the wearer an immediate reading of his or her radiation exposure. It also has the advantage of being reusable. The limited range, inability to provide a permanent record, and the potential for discharging and reading loss due to dropping or bumping are a few of the main disadvantages of a pocket dosimeter.

The two types commonly used in industrial radiography are the Direct Read Pocket Dosimeter and the Digital Electronic Dosimeter.

*Direct Read Pocket Dosimeter*

A direct reading pocket ionization dosimeter is generally of the size and shape of a fountain pen. The accumulated dose value can be read by pointing the instrument at a light source and observing the internal fiber through a system of built-in lenses. The fiber is viewed on a translucent scale which is graduated in units of exposure. Typical industrial radiography pocket dosimeters have a full scale reading of *200 mR* but there are designs that will record higher amounts. During the shift, the dosimeter reading should be checked frequently. The measured exposure should be recorded at the end of each shift.




*Digital Electronic Dosimeter*

These dosimeters measure both dose information and dose rate and display them in digital form. Also, some Digital Electronic Dosimeters include an audible alarm feature which emits an audible signal or chirp with each recorded increment of exposure. Consequently, the frequency or chirp rate of the alarm is proportional to the radiation intensity. Some models can also be set to provide a continuous audible signal when a preset exposure has been reached.

***Film Badges***


Personnel dosimetry film badges are commonly used to measure and record radiation exposure due to gamma rays, X-rays and beta particles. The detector is, as the name implies, a piece of radiation sensitive film. The film is packaged in a light proof, vapor proof envelope preventing light, moisture or chemical vapors from affecting the film. Film badges need to be worn correctly so that the dose they receive accurately represents the dose the wearer receives. Whole body badges are worn on the body between the neck and the waist, often on the belt or a shirt pocket.

The film is contained inside a film holder or badge. The badge incorporates a series of filters to determine the quality of the radiation. Radiation of a given energy is attenuated to a different extent by various types of absorbers. Therefore, the same quantity of radiation incident on the badge will produce a different degree of darkening under each filter. By comparing these results, the energy of the radiation

can be determined and the dose can be calculated knowing the film response for that energy. The badge holder also contains an open window to determine radiation exposure due to beta particles (*since beta particles are shielded by a thin amount of material*).

The major advantages of a film badge as a personnel monitoring device are that it provides a permanent record, it is able to distinguish between different energies of photons, and it can measure doses due to different types of radiation. It is quite accurate for exposures greater than 100 *mR*. The major disadvantages are that it must be developed and read by a processor (*which is time consuming*) and prolonged heat exposure can affect the film.

### *Thermoluminescent Dosimeter (TLD)*

Thermoluminescent dosimeters (*TLD*) are often used instead of the film badge. Like a film badge, it is worn for a period of time (*usually 3 months or less*) and then must be processed to determine the dose received, if any. *TLD*s can measure doses as low as *1 mR* and they have a precision of approximately 15% for low doses which improves to approximately 3% for high doses. *TLD*s are reusable, which is an advantage over film badges. However, no permanent record or re-readability is provided and an immediate, on the job readout is not possible.

A *TLD* has a phosphor, such as lithium fluoride (LiF) or calcium fluoride (CaF), in a solid crystal structure. When a *TLD* it is exposed to ionizing radiation at ambient temperatures, the radiation interacts with the phosphor crystal causing some of the atoms in the material to produce free electrons and become ionized. The free electrons are trapped and locked into place in the imperfections in the crystal lattice structure.

Heating the crystal causes the crystal lattice to vibrate, releasing the trapped electrons in the process. Released electrons return to the original ground state, releasing the captured energy from ionization as light, hence the name thermoluminescent. Instead of reading the optical density (blackness) of a film, as is done with film badges, the amount of light released versus the heating of the individual pieces of thermoluminescent material is measured. The “glow curve” produced by this process is then related to the radiation exposure. The process can be repeated many times.

## Safety Controls

Since X-ray and gamma radiation are not detectable by the human senses and the resulting damage to the body is not immediately apparent, a variety of safety controls are used to limit exposure. The two basic types of radiation safety controls used to provide a safe working environment are engineered and administrative controls. Engineered controls include shielding, interlocks, alarms, warning signals, and material containment. Administrative controls include postings, procedures, dosimetry, and training.

Engineered controls such as shielding and door interlocks are used to contain the radiation in a cabinet or a "radiation vault". Fixed shielding materials are commonly high density concrete and/or lead. Door interlocks are used to immediately cut the power to X-ray generating equipment if a door is accidentally opened when X-rays are being produced. Warning lights are used to alert workers and the public that radiation is being used. Sensors and warning alarms are often used to signal that a predetermined amount of radiation is present. Safety controls should never be tampered with or bypassed.

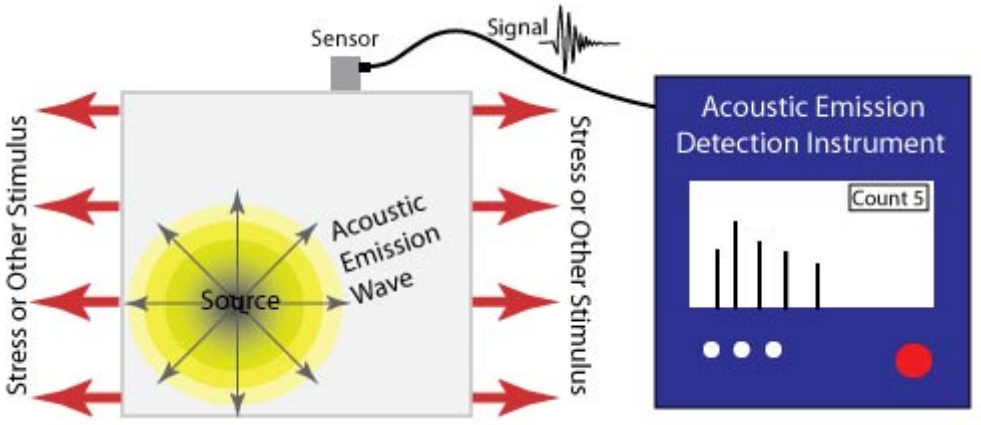
When portable radiography is performed, most often it is not practical to place alarms or warning lights in the exposure area. Ropes (*or cordon off tape*) and signs are used to block the entrance to radiation areas and to alert the public to the presence of radiation. Occasionally, radiographers will use battery operated flashing lights to alert the public to the presence of radiation.


Safety regulations classify the areas surrounding the location where ionizing radiation is present into restricted areas and controlled areas according to the radiation intensity level:

*Restricted areas*: Areas with a dose rate higher than *300 mR/h* must be secure so that nobody can enter this area. If anybody accidently enters this area, radiation must be terminated and the person must be checked. Access is only permitted under specific conditions and if there is an absolute need for it, the body dose should be calculated and the personal dose measured.

*Control areas*: These are areas with dose rates which are equivalent to or higher than *0.75 mR/h*. Control areas must be cordoned off and provided with a radiation warning signs.

# Introduction to Acoustic Emission Testing




Acoustic Emission (AE) refers to the generation of transient elastic waves produced by a sudden redistribution of stress in a material. When a structure is subjected to an external stimulus (change in pressure, load, or temperature), localized sources trigger the release of energy, in the form of stress waves, which propagate to the surface and are recorded by sensors. 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 rockbursts 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 and debonding 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 (AET), 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.

Acoustic Emission is unlike most other nondestructive testing (NDT) techniques in two regards. The first difference pertains to the origin of the signal. Instead of supplying energy to the object under examination, AET simply listens for the energy released by the object. AE tests are often performed on structures while in operation, as this provides adequate loading for propagating defects and triggering acoustic emissions.

The second difference is that AET deals with dynamic processes, or changes, in a material. This is particularly meaningful because only active features (e.g. crack growth) are highlighted. The ability to discern between developing and stagnant defects is significant. However, it is possible for flaws to go undetected altogether if the loading is not high enough to cause an acoustic event. Furthermore, AE testing usually provides an immediate indication relating to the strength or risk of failure of a component. Other advantages of AET include fast and complete volumetric inspection using multiple sensors,

permanent sensor mounting for process control, and no need to disassemble and clean a specimen.

Unfortunately, AE systems can only qualitatively gauge how much damage is contained in a structure. In order to obtain quantitative results about size, depth, and overall acceptability of a part, other NDT methods (often ultrasonic testing) are necessary. Another drawback of AE stems from loud service environments which contribute extraneous noise to the signals. For successful applications, signal discrimination and noise reduction are crucial.

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# Theory - AE Sources

As mentioned in the Introduction, acoustic emissions can result from the initiation and growth of cracks, slip and dislocation movements, twinning, or phase transformations in metals. In any case, AE's originate with stress. When a stress is exerted on a material, a strain is induced in the material as well. 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 plastic deformation or when a material is loaded at or near its yield stress. On the microscopic level, as plastic deformation occurs, atomic planes slip past each other through the movement of dislocations. 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 tip can be several times higher than the surrounding area. Therefore, AE activity will also 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.

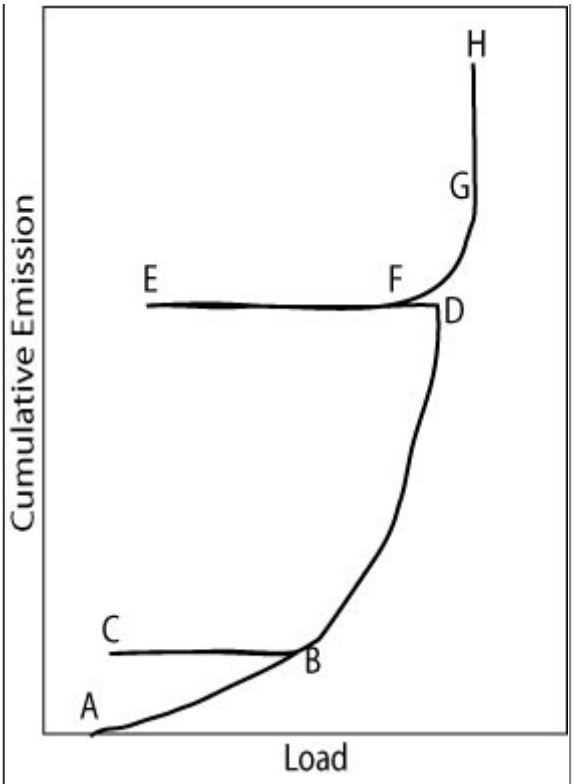
The amount of energy released by an acoustic emission and the amplitude of the waveform are related to the magnitude and velocity of the source event. The amplitude of the emission is proportional to the velocity of crack propagation and the amount of surface area created. Large, discrete crack jumps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

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

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



Basic AE history plot showing Kaiser effect (BCB), Felicity effect (DEF), and emission during hold (GH) 2

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. Another guideline governing AE's is the Dunegan corollary, which states that if acoustic emissions are observed prior to a previous maximum load, some type of new damage must have occurred. (Note: Time dependent processes like corrosion and hydrogen embrittlement tend to render the Kaiser Effect useless)

**Noise**

The sensitivity of an acoustic emission system is often limited by the amount of background noise nearby. 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).

**Pseudo Sources**

In addition to the AE source mechanisms described above, pseudo source mechanisms produce AE signals that are detected by AE equipment. Examples

include liquefaction and solidification, friction in rotating bearings, solid-solid phase transformations, leaks, cavitation, and the realignment or growth of magnetic domains (See Barkhausen Effect).

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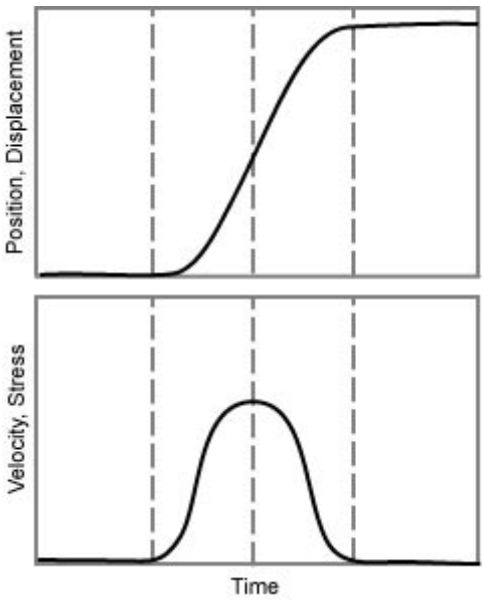
# Theory - Acoustic Waves

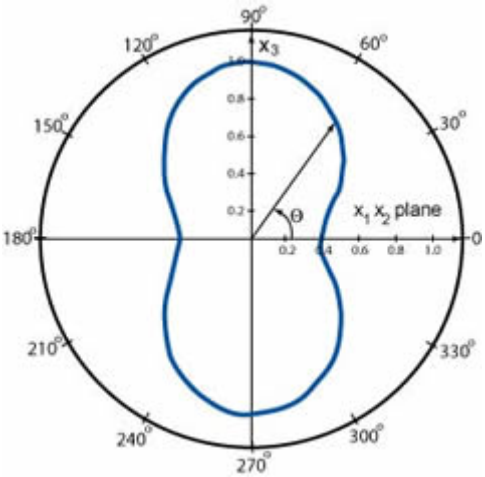
## Wave Propagation

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. The amplitude and energy of the primitive pulse vary over an enormous range from submicroscopic dislocation movements to gross crack jumps.




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.

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.




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

As these primitive waves travel through a material, their form is changed considerably. Elastic wave source and elastic wave motion theories are being investigated to determine the complicated relationship between the AE source pulse and the corresponding movement at the detection site. The ultimate goal of studies of the interaction between elastic waves and material structure is to accurately develop a description of the source event from the output signal of a distant sensor.

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. More information on sensors will be discussed later in the Equipment section.

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.

**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%. This can be traced back to the simple conservation of energy. Another cause of attenuation is material damping, as alluded to in the previous paragraph. While an AE wave passes through a material, its elastic and kinetic energies are absorbed and converted into heat. The third cause of attenuation is wave scattering. Geometric discontinuities (e.g. twin boundaries, nonmetallic inclusions, or grain boundaries) and structural boundaries both reflect some of the wave energy that was initially transmitted.

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 the type of AE signal produced by a crack. By using this method, 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.

**Wave Mode and Velocity**

As mentioned earlier, using AE inspection in conjunction with other NDE techniques can be an effective method in gauging the location and nature of defects. Since source locations are determined by the time required for the wave to travel through the material to a sensor, it is important that the velocity of the propagating waves be accurately calculated. This is not an easy task since wave propagation depends on the material in question and the wave mode being detected. For many applications, Lamb waves are of primary concern because they are able to give the best indication of wave propagation from a source whose distance from the sensor is larger than the thickness of the material. For additional information on Lamb waves, see the wave mode page in the Ultrasonic Inspection section.

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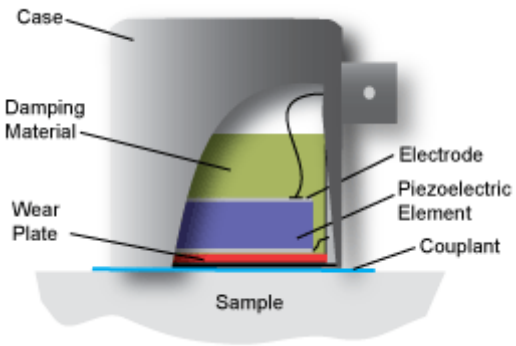
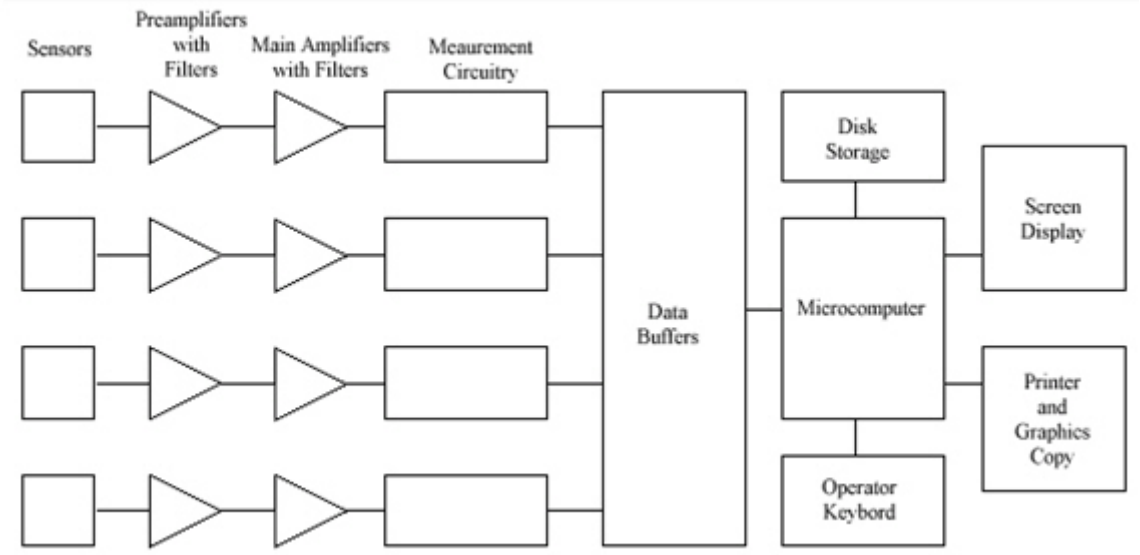
# Equipment




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. The opposite holds true as well.

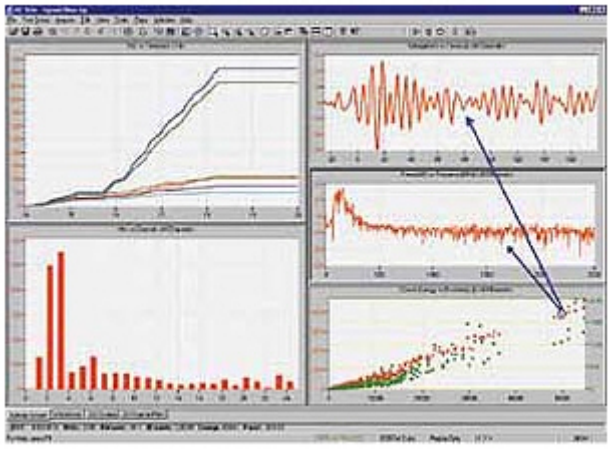
Ideally, the AE signal that reaches the mainframe will be free of background noise and electromagnetic interference. Unfortunately, this is not realistic. However, sensors and preamplifiers are designed to help eliminate unwanted signals. First, the preamplifier boosts the voltage to provide gain and 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 bandpass filter for elimination of low frequencies (common to background noise) and high frequencies. Following completion of this process, the signal travels to the acoustic system mainframe and eventually to a computer or similar device for analysis and storage. Depending on noise conditions, further filtering or amplification at the mainframe may still be necessary.




Schematic Diagram of a Basic Four-channel Acoustic Emission Testing System

After passing the AE system mainframe, the signal comes to a detection/measurement circuit as shown in the figure directly above. Note that multiple-measurement circuits can be used in multiple sensor/channel systems for source location purposes (to be described later). 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 either continuous (analogous to Gaussian, random noise with amplitudes varying according to the magnitude of the AE events) or burst-type. Each time the threshold voltage is exceeded, the measurement circuit releases a digital pulse. The first pulse is used to signify the beginning of a hit. (A hit is used to describe the AE event that is detected by a particular sensor. One AE event can cause a system with numerous channels to record multiple hits.) Pulses will continue to be generated while the signal exceeds the threshold voltage. Once this process has stopped for a predetermined amount of time, the hit is finished (as far as the circuitry is concerned). The data from the hit is then read into a microcomputer and the measurement circuit is reset.

## Hit Driven AE Systems and Measurement of Signal Features



Although several AE system designs are available (combining various options, sensitivity, and cost), most AE systems use a hit-driven architecture. The hit-driven design is able to efficiently measure all detected signals and record digital descriptions for each individual feature (detailed later in this section). During periods of inactivity, the system lies dormant. Once a new signal is detected, the system records the hit or hits, and the data is logged for present and/or future display.

Also common to most AE systems is the ability to perform routine tasks that are valuable for AE inspection. These tasks include quantitative signal measurements with corresponding time and/or load readings, discrimination between real and false signals (noise), and the collection of statistical information about the parameters of each signal.

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# AE Source Location Techniques

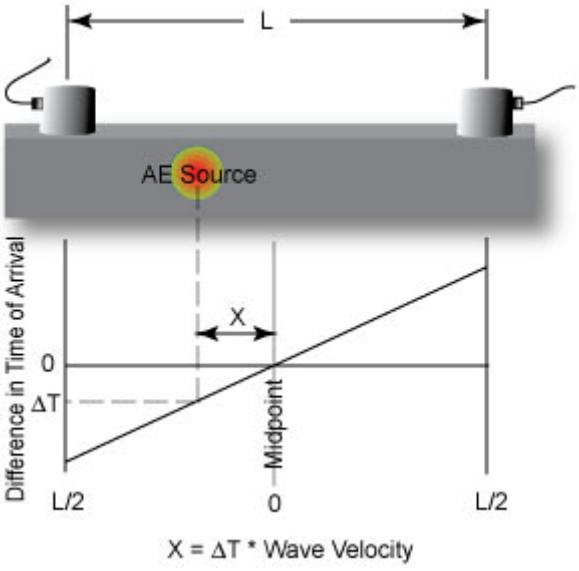
## Multi-Channel Source Location Techniques:

Locating the source of significant acoustic emissions is often the main goal of an inspection. Although the magnitude of the damage may be unknown after AE analysis, follow up testing at source locations can provide these answers. As previously mentioned, many AE systems are capable of using multiple sensors/channels during testing, allowing them to record a hit from a single AE event. These AE systems can be used to determine the location of an event source. As hits are recorded by each sensor/channel, the source can be located by knowing the velocity of the wave in the material and the difference in hit arrival times among the sensors, as measured by hardware circuitry or computer software. By properly spacing the sensors in this manner, 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. 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.

## Linear Location Technique

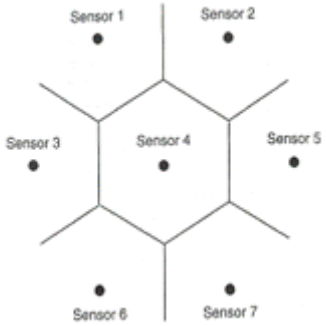
Several source location techniques have been developed based on this method. One of the commonly used computed-source location techniques is the linear location principle shown to the right. Linear location is often used to evaluate struts on truss bridges. When the source is located at the midpoint, 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.

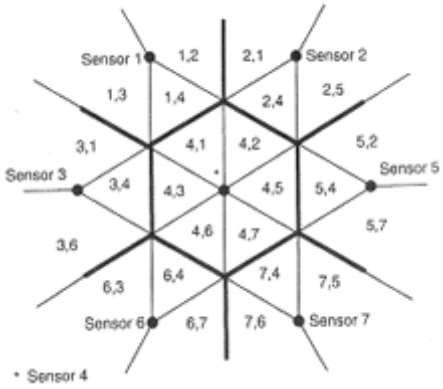



Because the above scenario implicitly assumes that the source is on a line passing through the two sensors, it is only valid for a linear problem. When using AE to identify a source location in a planar material, three or more sensors are used, and the optimal position of the source is between the sensors. Two categories of source location analysis are used for this situation: zonal location and point location.

## Zonal Location Technique

As the name implies, zonal location aims to trace the waves to a specific zone or region around a sensor. This method is used in anisotropic materials or in other structures where sensors are spaced relatively far apart or when high material attenuation affects the quality of signals at multiple sensors. Zones can be lengths, areas or volumes depending on the dimensions of the array. A planar sensor array with detection by one sensor is shown in the upper right figure. The source can be assumed to be within the region and less than halfway between sensors.

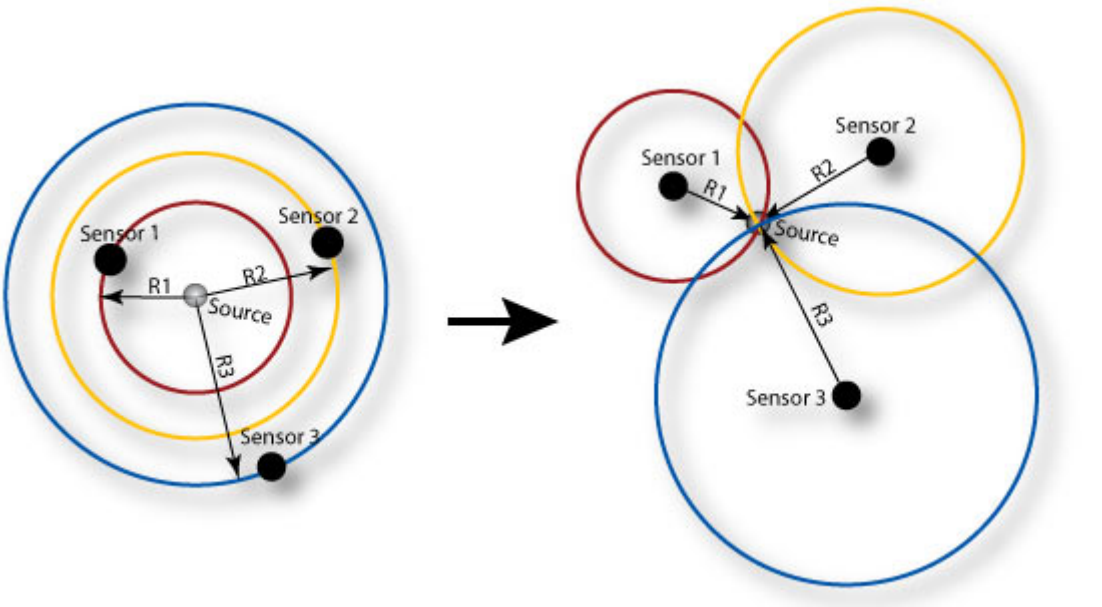



When additional sensors are applied, arrival times and amplitudes help pinpoint the source zone. The ordered pair in lower right figure represents the two sensors detecting the signal in the zone and the order of signal arrival at each sensor. When relating signal strength to peak amplitude, the largest peak amplitude is assumed to come from the nearest sensor, second largest from the next closest sensor and so forth.

## 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. Equations can then be derived using sensor array geometry or more complex algebra to locate more specific points of interest.

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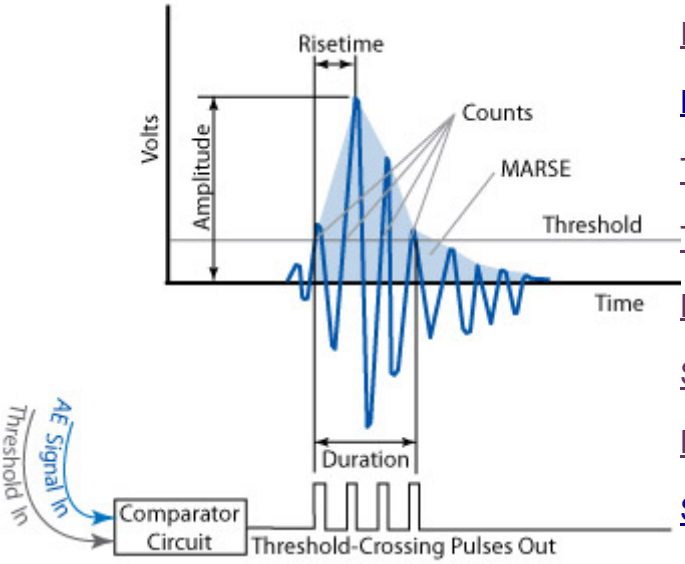
# AE Signal Features




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 then 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.

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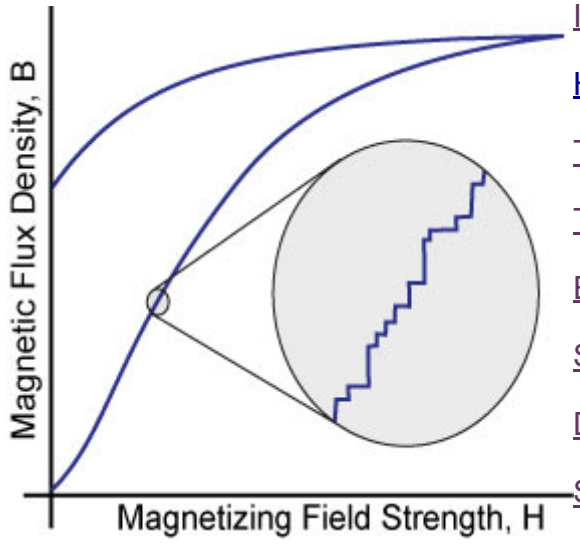
# AE Barkhausen Techniques

## Barkhausen Effect

The Barkhausen effect refers to the sudden change in size of ferromagnetic domains that occur during magnetization or demagnetization. During magnetization, favorably oriented domains develop at the cost of less favorably oriented domains. These two factors result in minute jumps of magnetization when a ferromagnetic sample (e.g. iron) is exposed to an increasing magnetic field (see figure). Domain wall motion itself is determined by many factors like microstructure, grain boundaries, inclusions, and stress and strain. By the same token, the Barkhausen effect is too a function of stress and strain.




## Barkhausen Noise

Barkhausen noise can be heard if a coil of wire is wrapped around the sample undergoing magnetization. Abrupt movements in the magnetic field produce spiking current pulses in the coil. When amplified, the clicks can be compared to Rice Krispies or the crumbling a candy wrapper. The amount of Barkhausen noise is influenced by material imperfections and dislocations and is likewise dependent on the mechanical properties of a material. Currently, materials exposed to high energy particles (nuclear reactors) or cyclic mechanical stresses (pipelines) are available for nondestructive evaluation using Barkhausen noise, one of the many branches of AE testing.

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# Applications

Acoustic emission is a very versatile, non-invasive way to gather information about a material or structure. Acoustic Emission testing (AET) is be 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.

## Weld 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. Amazingly, cracking can continue for up to 10 days after the weld has been completed. Using stainless steel welds with known inclusions and accelerometers for detection purposes and background noise monitoring, it was found by W. D. Jolly (1969) that low level signals and more sizeable bursts were related to the growth of microfissures and larger cracks respectively. ASTM E 749-96 is a standard practice of AE monitoring of continuous welding.

## Bucket Truck (Cherry Pickers) Integrity Evaluation

Accidents, overloads and fatigue can all occur when operating bucket trucks or other aerial equipment. If a mechanical or structural defect is ignored, serious injury or fatality can result. In 1976, the Georgia Power Company pioneered the aerial manlift device inspection. Testing by independent labs and electrical utilities followed. Although 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.

## Gas Trailer Tubes

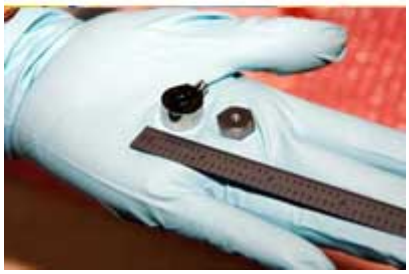
Acoustic emission testing on pressurized jumbo tube trailers was authorized by the Department of Transportation in 1983. Instead of using hydrostatic retesting, where tubes must be removed from service and disassembled, AET allows for in situ testing. A 10% over-pressurization is performed at a normal 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. Because of the high stresses in the circumferential direction of the tubes, tests are geared toward finding longitudinal fatigue cracks.

## 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 about every two years and when damage is detected, the bridge is either shut down, its weight capacity is lowered, or it is singled out for more frequent monitoring. Acoustic Emission is increasingly being used for bridge monitoring applications because it can continuously gather data and detect changes that may be due to damage without requiring lane closures or bridge shutdown. In fact, traffic flow is commonly used to load or stress the bridge for the AE testing.

## Aerospace Structures



Most aerospace structures consist of complex assemblies of components that have been design to carry significant loads while being as light as possible. This combination of requirements leads to many parts that can tolerate only a minor amount of damage before failing. This fact makes detection of damage extremely important but components are often packed tightly together making access for inspections difficult. 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. AET has been used in laboratory structural tests, as well as in flight test applications. NASA's Wing Leading Edge Impact Detection System is partially based on AE technology. The image to 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.

## Others

- Fiber-reinforced polymer-matrix composites, in particular glass-fiber reinforced parts or structures (e.g. fan blades)
- Material research (e.g. investigation of material properties, breakdown mechanisms, and damage behavior)
- Inspection and quality assurance, (e.g. wood drying processes, scratch tests)
- Real-time 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

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.

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This article provides answers to the following questions, among others:

- How does eddy current testing work?
- Why are two induction coils often connected against to each other?

With *eddy current testing*, electrically conductive materials can be examined for pores, inclusions and cracks in the area near the surface. Layer thickness and microstructure tests are also possible with this method.


*Figure: Measuring tool for eddy current testing*

Eddy current testing is based on the principle of electromagnetic induction. For this purpose, a constantly changing magnetic field (*primary field*) is first generated in an *field coil* by an alternating current.

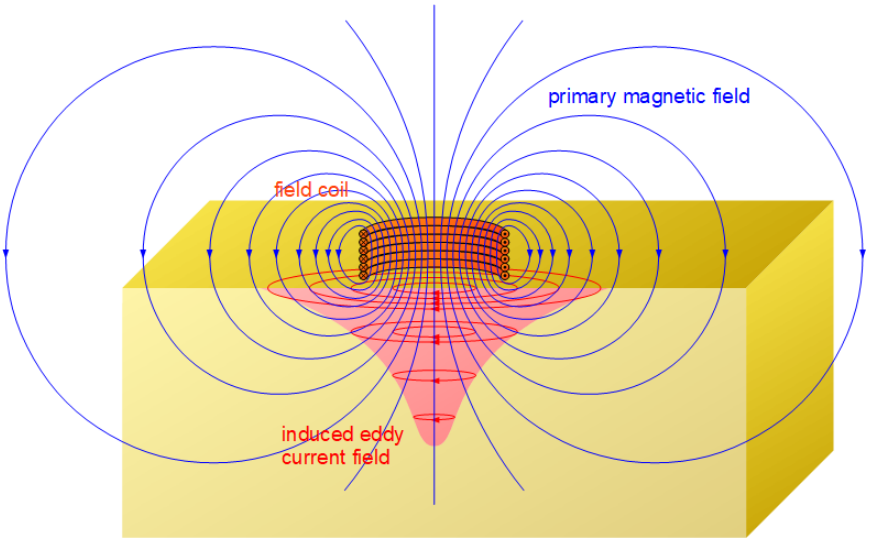



*Figure: Induction of eddy currents by primary magnetic field*

This alternating magnetic field induces an annular current flow near a metallic surface, also known as *eddy current*. This eddy current also changes constantly in accordance with the alternating primary magnetic field of the field coil. The eddy currents can be regarded analog to the circular currents of the field coil and thus also generate a magnetic field (*secondary field*).

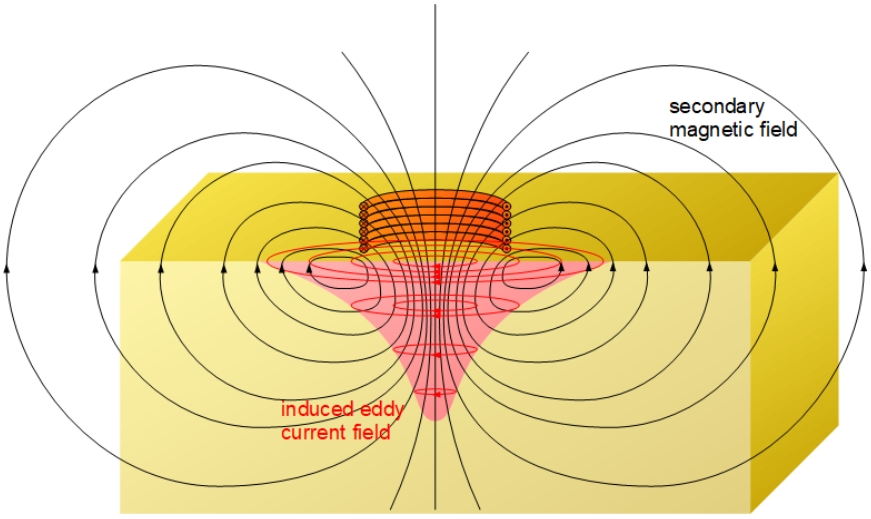



*Figure: Secondary magnetic field induced by eddy currents*

The secondary magnetic field induced in the workpiece by eddy currents is directed in the opposite direction to the external primary magnetic field of the field coil (Lenz's law). The secondary field thus weakens the primary field and a somewhat weaker *overall magnetic field* is produced.

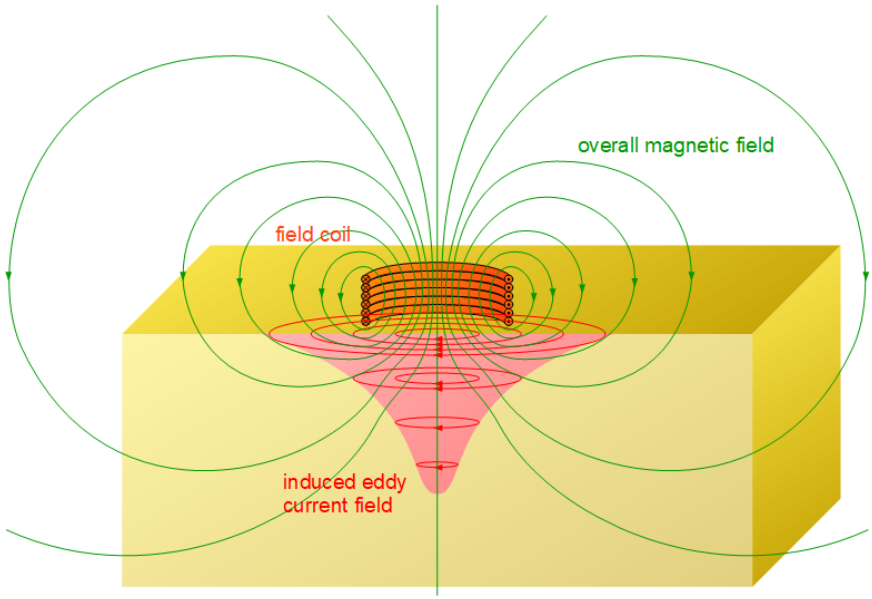



*Figure: Overall magnetic field as superposition of primary and secondary field*

Depending on how good or bad the surface to be tested conducts the current, more or less strong eddy currents are formed. This in turn has a direct effect on the strength of the secondary field and thus on the overall field. The magnetic properties of the surface to be tested also influence the secondary field and thus the overall field. At cracks, pores or other inclusions, the electrical and magnetic properties usually change very strongly, so that the total magnetic field changes there. The change of the magnetic field serves as proof of defects.

Note that ultimately only the overall magnetic field actually exists physically. The primary field and the secondary field itself do not exist, since they superpose and only the overall field will be present.

In order to detect the overall field or rather its change, the induction effect is again used. The constantly changing overall field creates an *induction voltage* in *induction coil* which is implemented in a *detector.* This induction voltage in the induction coil ultimately serves as a measurement value, since the induction voltage at the induction coil also changes as the overall magnetic field changes.

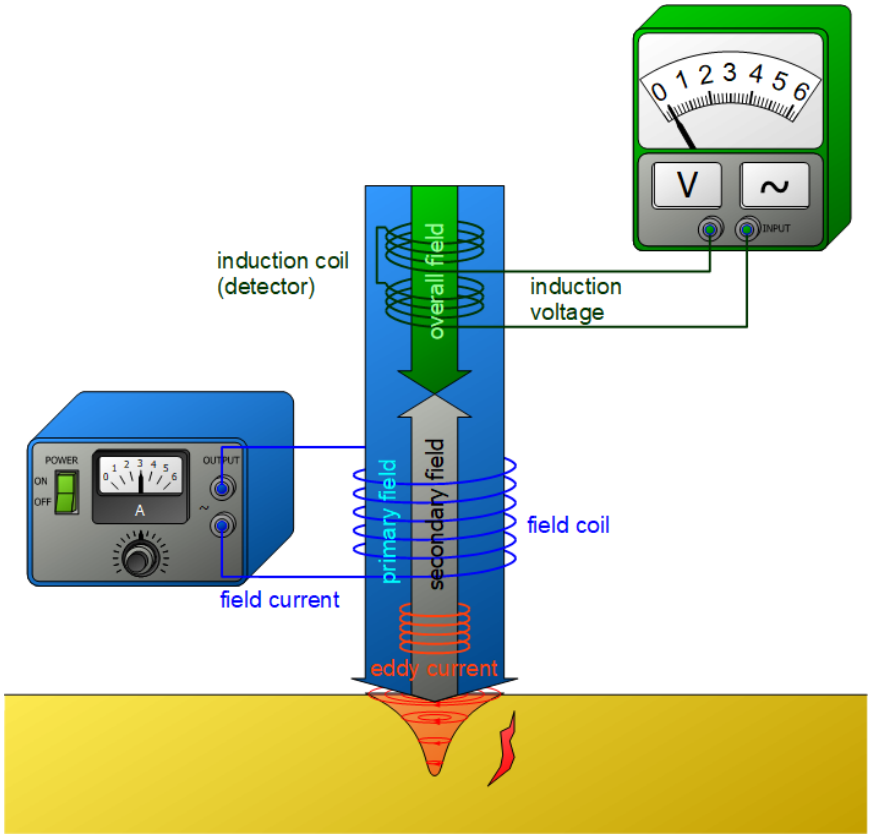
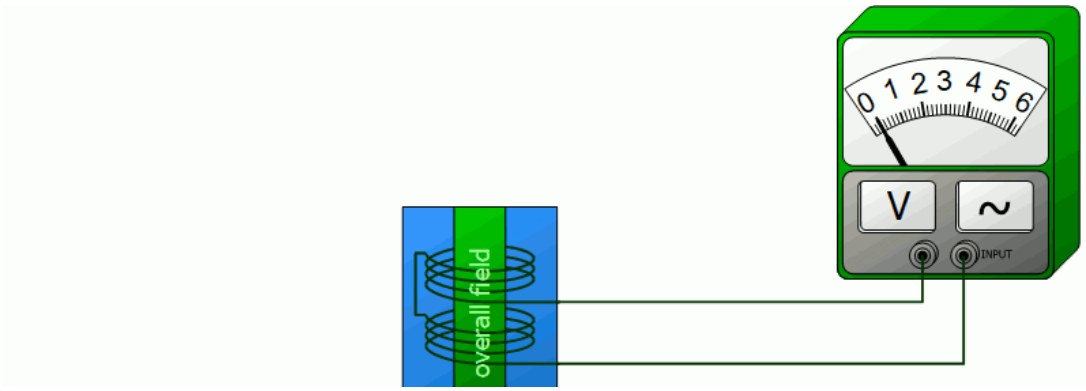
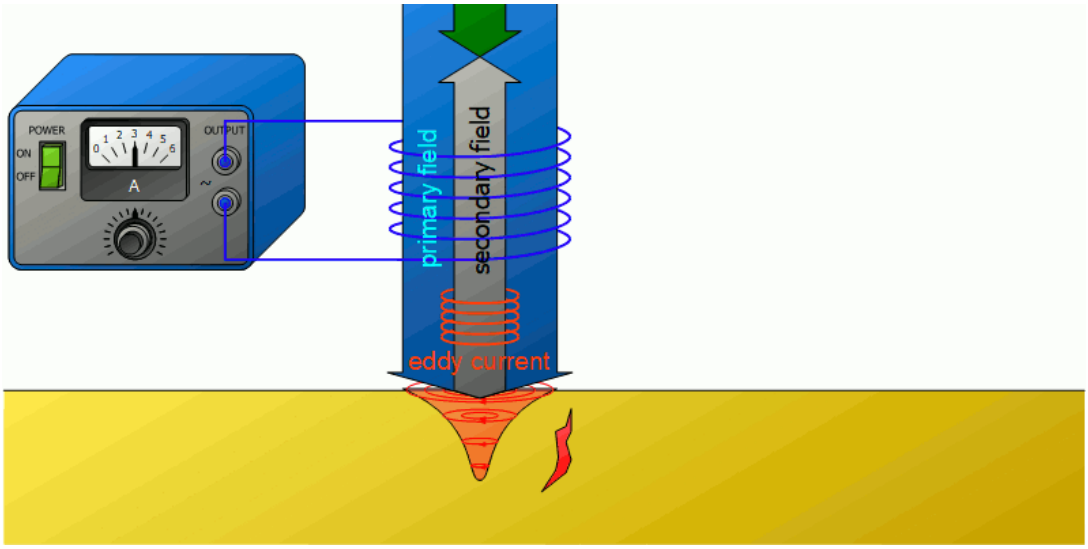



*Figure: Principle of eddy current testing*

The induction coil is integrated directly inside the field coil. To increase the measurement sensitivity, two induction coils can also be connected against each other. In this case, it is not the induction voltage of the induction coil that is measured, but the much more sensitive difference in the two induction coil voltages.






*Animation: Principle of eddy current testing*