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Department of Mechanical Engineering

&

Imaya Inspection Technology

VALUE ADDED COURSE ON WELDING AND INSPECTION TECHNIQUES

(MVA014)

SYLLABUS

Chapter 1: Liquid Penetrant Testing

Chapter 2: Magnetic Particle Testing

Chapter 3: Radiographic Testing

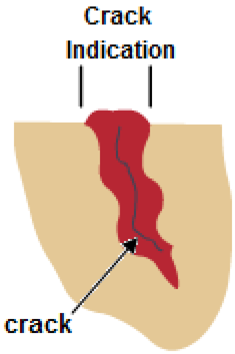
Chapter 4: Ultrasonic Testing

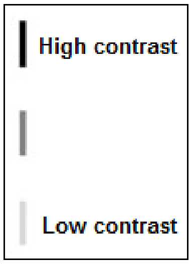
Liquid Penetrant Testing

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.*).

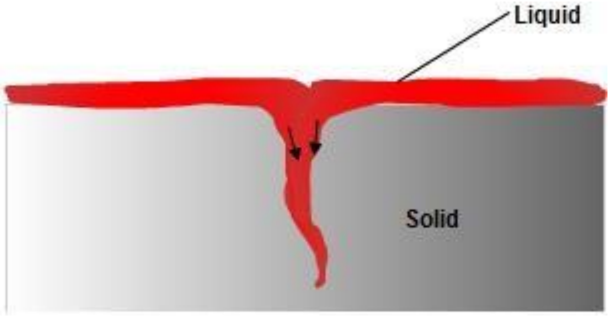
Steps of Liquid Penetrant Testing

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.

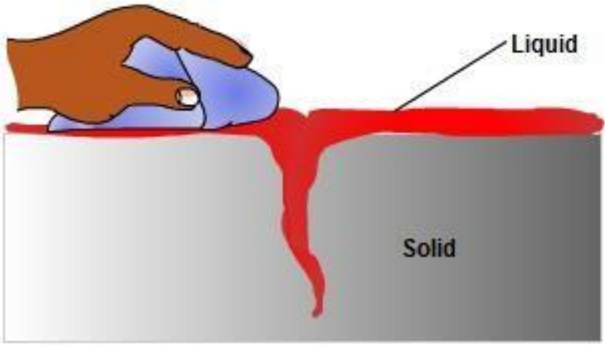
2. *Penetrant Application*: Once the surface has been thoroughly cleaned and dried, the penetrant material is applied by spraying, brushing, or immersing the part in a penetrant bath.

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.



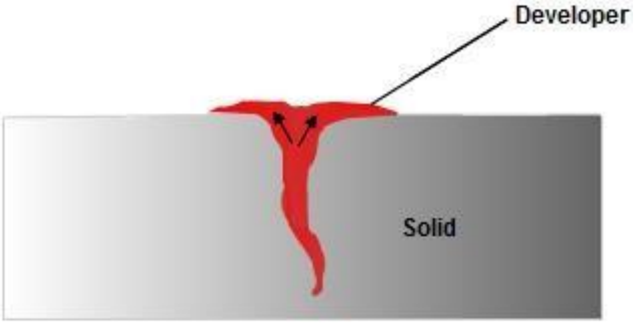
4. *Excess Penetrant Removal*: This is the most delicate step of the inspection procedure because the excess penetrant must be removed from the surface of the sample while removing as little penetrant as possible from defects.

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*).

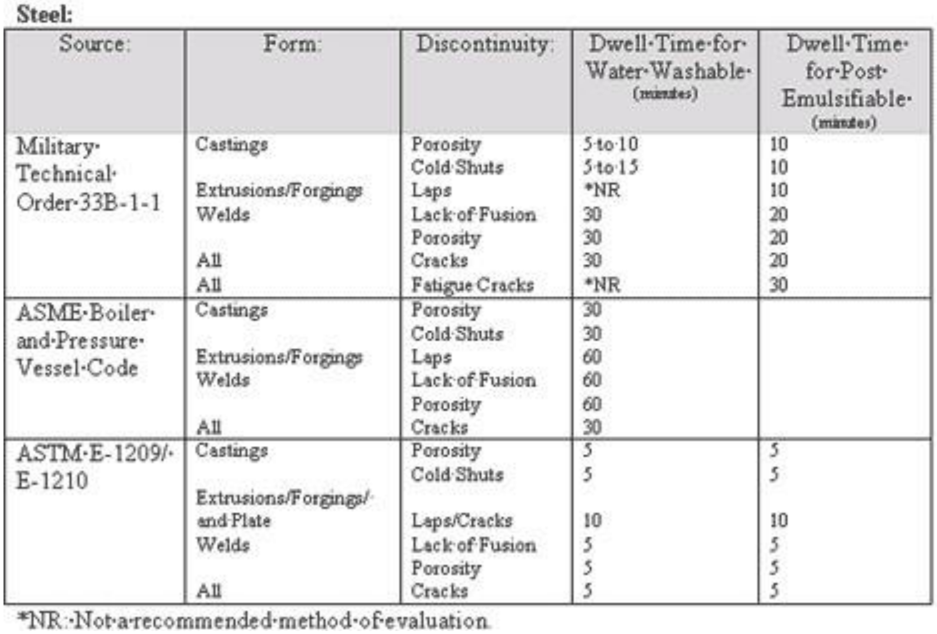
Penetrant Dwell Time

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 Easy to apply	Does not form contrast background so cannot be used with visible systems 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) Indications for water washable systems are dim and blurred
Suspendable	Ease of coating entire part Indications are bright and sharp 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 Easy to apply to readily accessible surfaces White coating of good contrast can be produced which work well for both visible and fluorescent systems Indications show-up rapidly and are well defined Provides highest sensitivity	Difficult to apply evenly to all surfaces 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 µW/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.

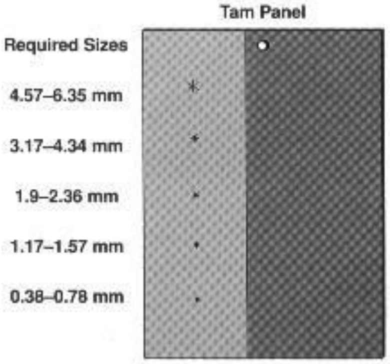
Light Measurement

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.

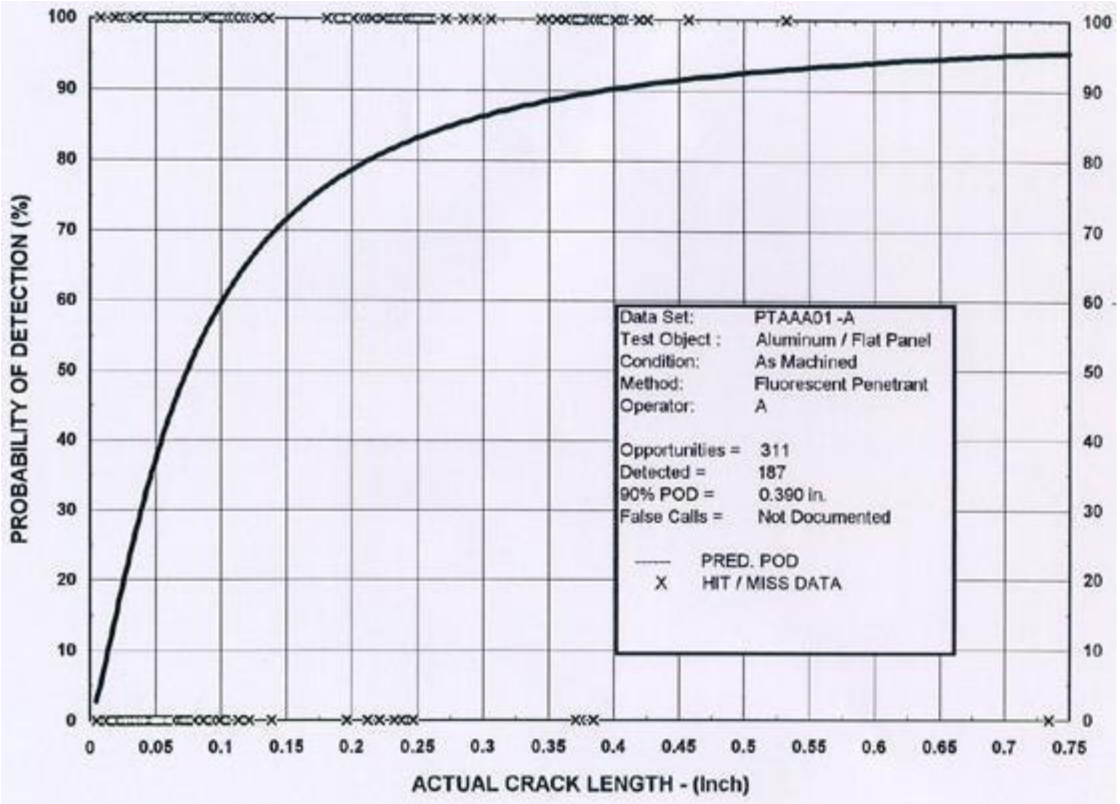
There are some universal test specimens that can be used if a reference part is not available. The most commonly used test specimen is the *TAM* or *PSM* panel which is used for fluorescent penetrant systems. These panels are usually made of stainless steel that has been chrome plated on one half and 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 <u>volume of the defect</u> 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

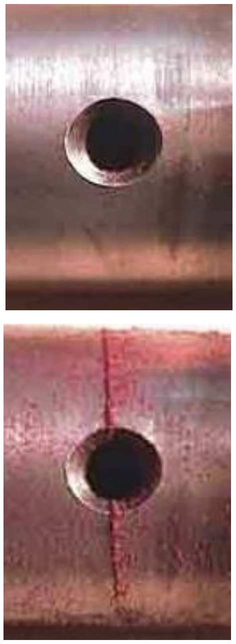
Whenever chemicals must be handled, certain precautions must be taken. Before working with a chemical of any kind, it is highly recommended that the material safety data sheets (MSDS) be reviewed so that proper chemical safety and hygiene practices can be followed. Some of the penetrant materials are 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

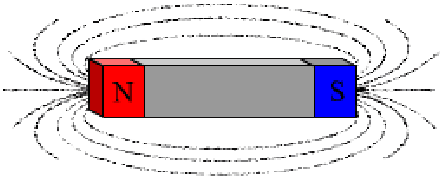
Magnetic particle testing is one of the most widely utilized NDT methods since it is fast and relatively easy to apply and part surface preparation is not as critical as it is for some other methods. This mithod uses magnetic fields and small magnetic particles (*i.e.iron filings*) to detect flaws in 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.



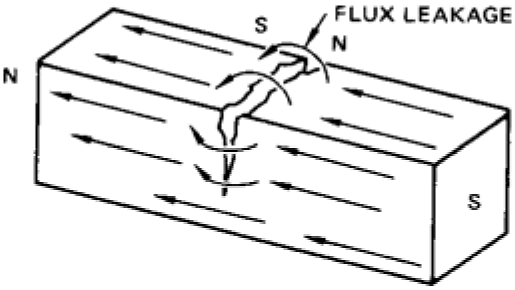
The method is used to inspect a variety of product forms including castings, forgings, and weldments. Many different industries use magnetic particle inspection such as structural steel, automotive, petrochemical, power generation, and aerospace industries. Underwater inspection is another area where 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*).

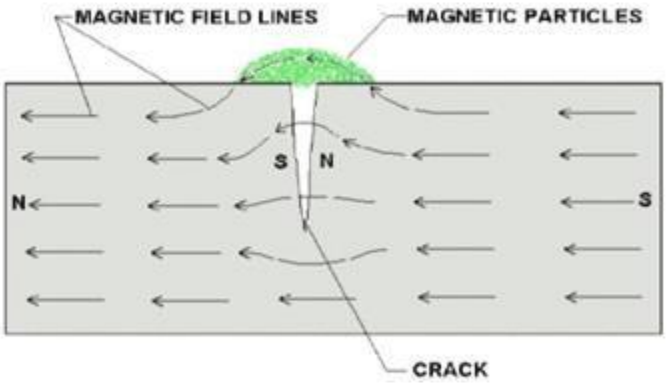


When a bar magnet is broken in the center of its length, two complete bar magnets with magnetic poles on each end of each piece will result. If the magnet is just cracked but not broken completely in two, a north and south pole will form at each edge of the crack. The magnetic field exits the north pole 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

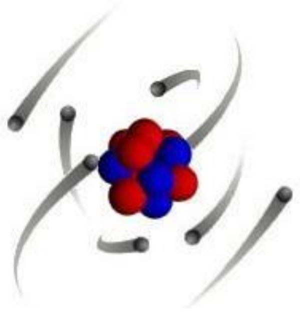
- High sensitivity (*small discontinuities can be detected*).
- Indications are produced directly on the surface of the part and constitute a visual representation of the flaw.
- Minimal surface preparation (*no need for paint removal*)
- Portable (*small portable equipment & materials available in spray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

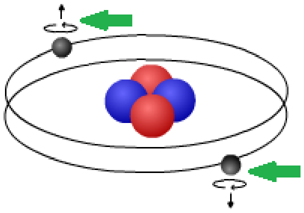


The source of magnetism lies in the basic building block of all matter, the atom. Atoms are composed of protons, neutrons and electrons. The protons and neutrons are located in the atom's nucleus and the electrons are in constant motion around the nucleus. Electrons carry a negative electrical charge 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.



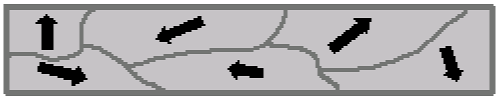
In most atoms, electrons occur in pairs where these pairs spin in opposite directions. The opposite spin directions of electron pairs cause their magnetic fields to cancel each other. Therefore, no net magnetic field exists. Alternately, materials with some unpaired electrons will have a net magnetic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

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

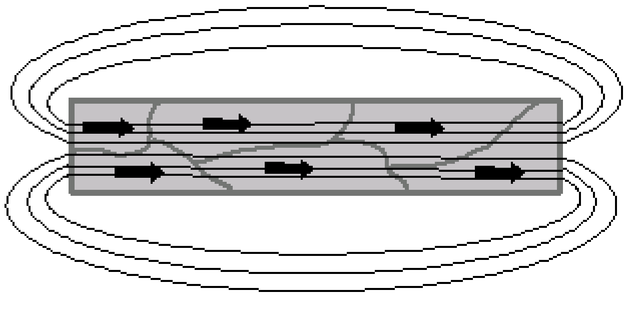
Diamagnetic materials which have a weak, negative susceptibility to magnetic fields. Diamagnetic materials are slightly repelled by a magnetic field and the material does not retain the magnetic properties when the external field is removed. In diamagnetic materials all the electrons are paired so there 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

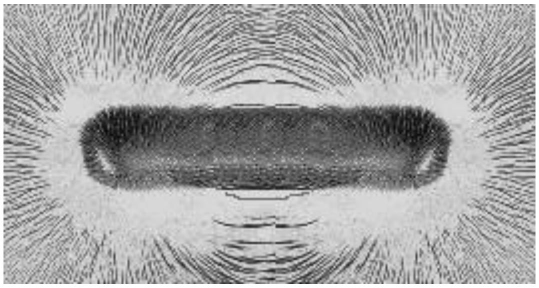


Magnetized Material

Magnetic Field Characteristics

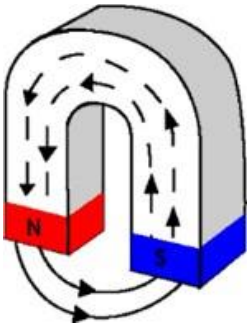
Magnetic Field In and Around a Bar Magnet

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

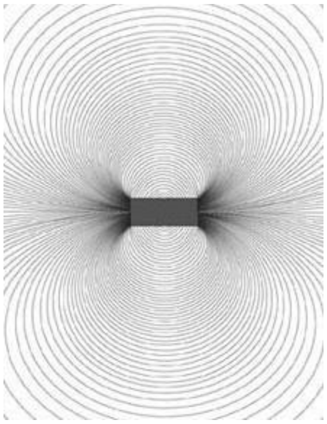
Magnets come in a variety of shapes and one of the more common is the horseshoe (U) magnet. The horseshoe magnet has north and south poles just like a bar magnet but the magnet is curved so the poles lie in the same plane. The magnetic lines of force flow from pole to pole just like in the bar magnet. 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

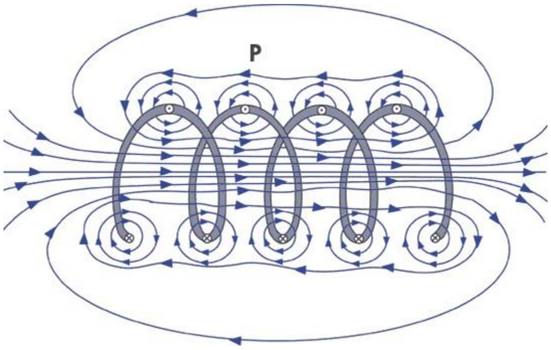
Magnets are not the only source of magnetic fields. The flow of electric current through a conductor generates a magnetic field. When electric current flows in a long straight wire, a circular magnetic field is generated around the wire and the intensity of this magnetic field is directly proportional 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

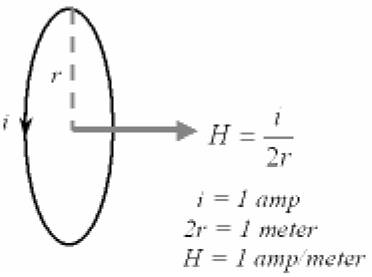
When a current carrying wire is formed into several loops to form a coil, the magnetic field circling each loop combines with the fields from the other loops to produce a concentrated field through the center of the coil (*the field flows along the longitudinal axis and circles back around the outside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

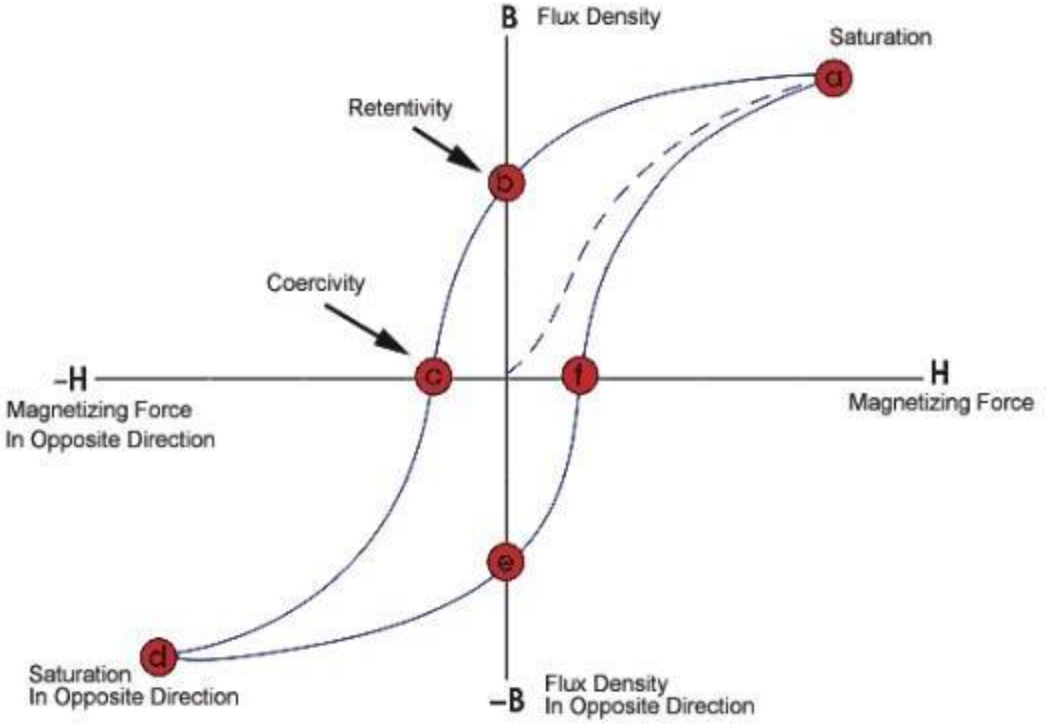


- The unit for magnetic *field strength* **H** is *ampere/meter* (*A/m*). A magnetic field strength of *1 A/m* is produced at the center of a single circular conductor with a *1 meter* diameter carrying a steady current of *1 ampere*.
- The number of magnetic lines of force cutting through a plane of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

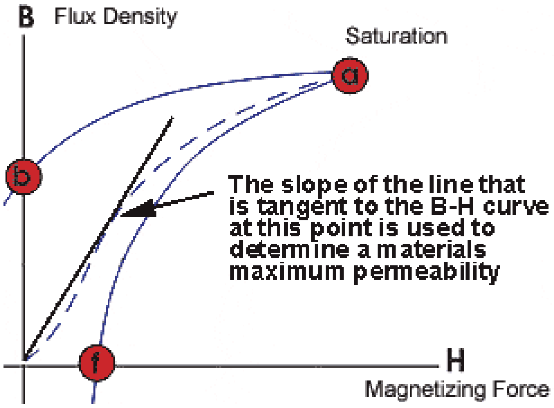
5. ***Reluctance*** - Is the opposition that a ferromagnetic material shows to the establishment of a magnetic field. Reluctance is analogous to the resistance in an electrical circuit.

Permeability

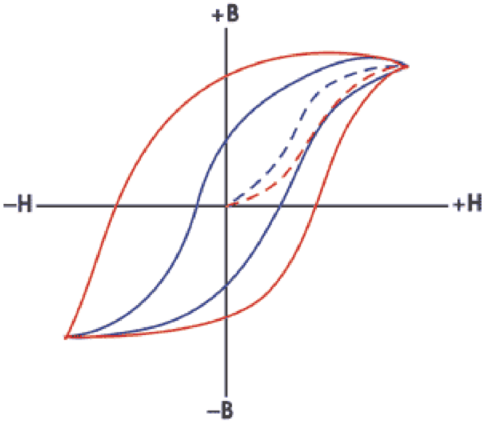
As previously mentioned, permeability (μ) is a material property that describes the ease with which a magnetic flux is established in a component. It is the ratio of the flux density (B) created within a material to the magnetizing field (H) and it is represented by the following equation:

$$\mu = B/H$$

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.



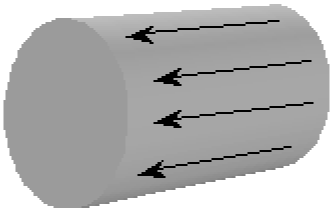
- Relative to other materials, a material with a wider hysteresis loop has:
  - Lower Permeability
  - Higher Retentivity
  - Higher Coercivity
  - Higher Reluctance
  - Higher Residual Magnetism
- Relative to other materials, a material with a narrower hysteresis loop has:
  - Higher Permeability
 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

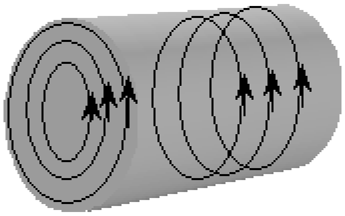
Magnetic Field Orientation and Flaw Detectability

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.

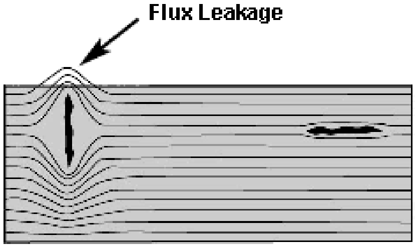
- *A longitudinal magnetic field* has magnetic lines of force that run parallel to the long axis of the part. Longitudinal magnetization of a component can be accomplished using the longitudinal field set up by a coil or solenoid. It can also be accomplished using permanent magnets or electromagnets.



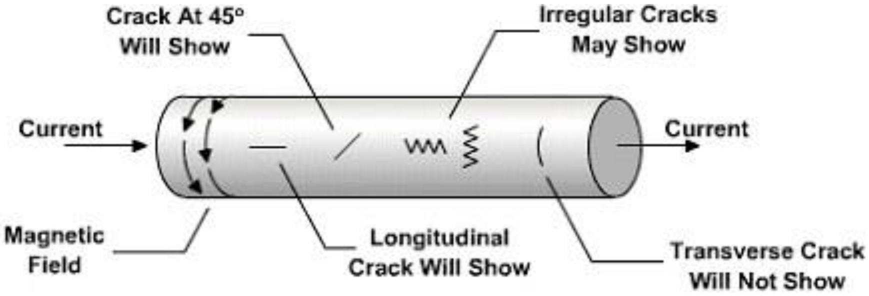
- *A circular magnetic field* has magnetic lines of force that run circumferentially around the perimeter of a part. A circular magnetic field is induced in an article by either passing current through the component or by passing current through a conductor surrounded by the component.



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

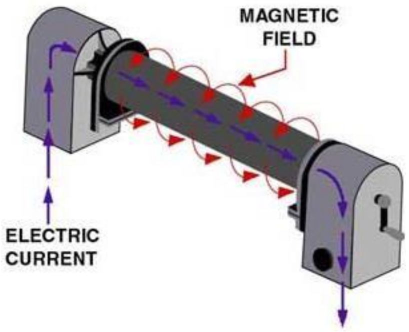
There are a variety of methods that can be used to establish a magnetic field in a component for evaluation using magnetic particle inspection. It is common to classify the magnetizing methods as either direct or indirect.

Magnetization Using Direct Induction (Direct Magnetization)

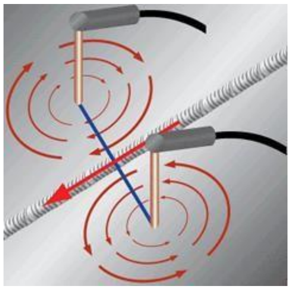
With direct magnetization, current is passed directly through the component. The flow of current causes a circular magnetic field to form in and around the conductor. When using the direct magnetization method, care must be taken to ensure that good electrical contact is established and maintained between 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.

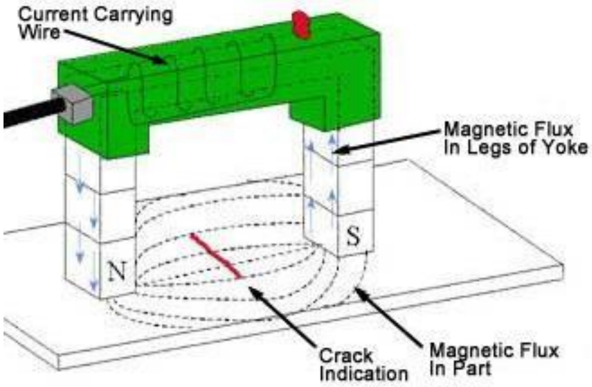


Magnetization Using Indirect Induction (Indirect Magnetization)

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.

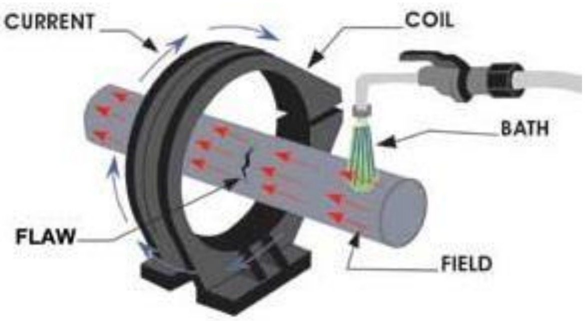
- The use of *permanent magnets* is a low cost method of establishing a magnetic field. However, their use is limited due to lack of control of the field strength and the difficulty of placing and removing strong permanent magnets from the component.

- *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

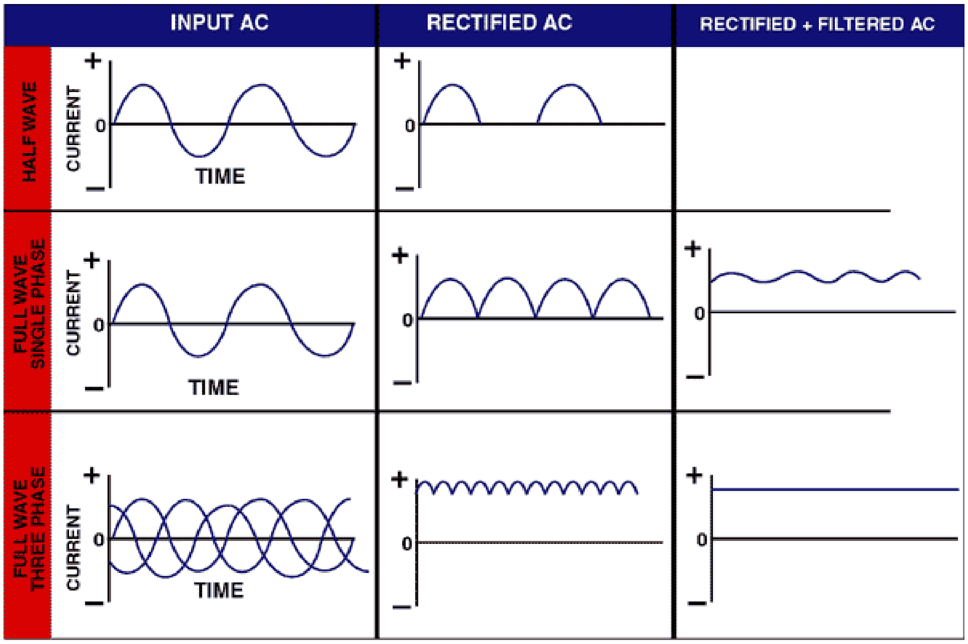
Direct current (DC) flows continuously in one direction at a constant voltage. A battery is the most common source of direct current. The current is said to flow from the positive to the negative terminal, though electrons flow in the opposite direction. DC is very desirable when inspecting for subsurface 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.

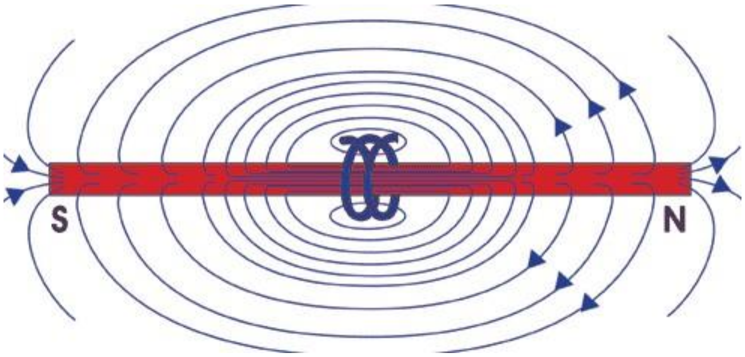
Three Phase Full Wave Rectified Alternating Current

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*).

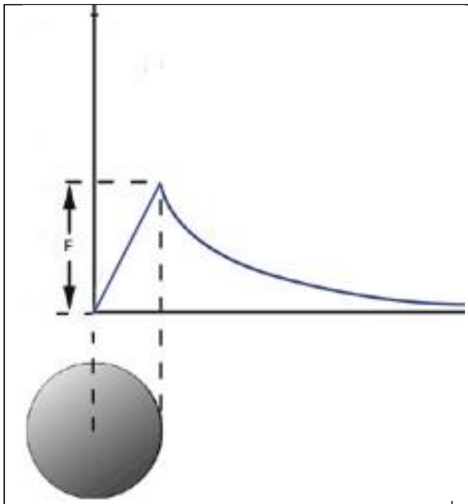
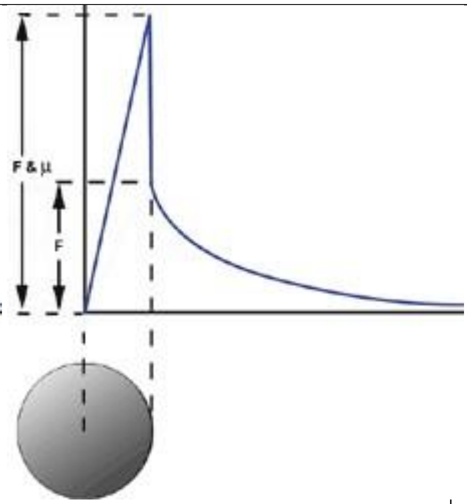
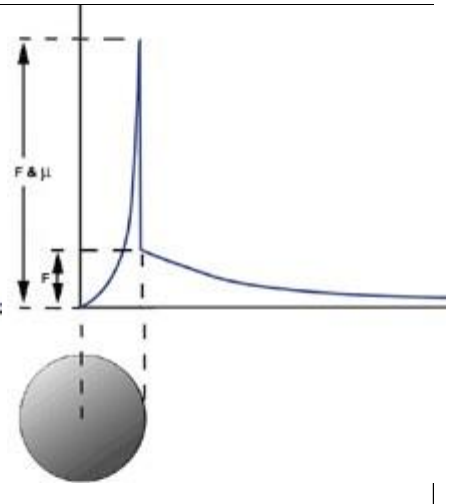
- The field strength inside the conductor is dependent on the current strength, magnetic permeability of the material, and, if ferromagnetic, the location on the B-H curve.
- The field strength outside the conductor is directly proportional to the current strength and it decreases with distance from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

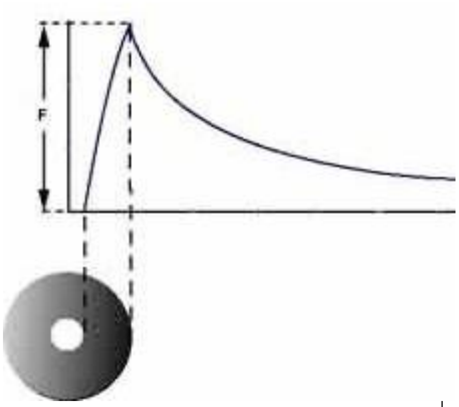
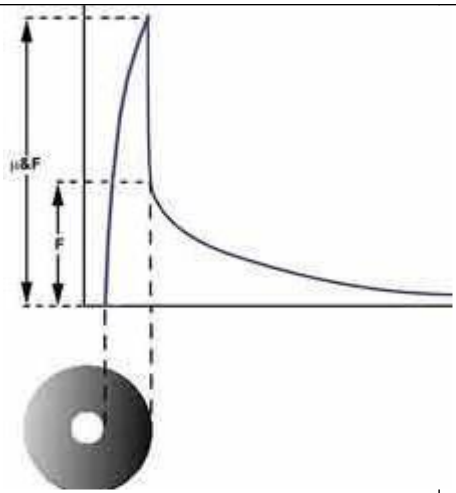
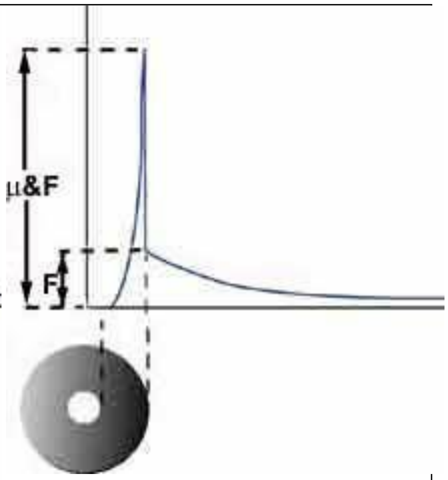
- When the magnetic conductor is carrying AC, the internal magnetic field will be concentrated in a thin layer near the surface of the conductor (*skin effect*). The external field decreases with increasing distance from the surface same as with DC.

		
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.

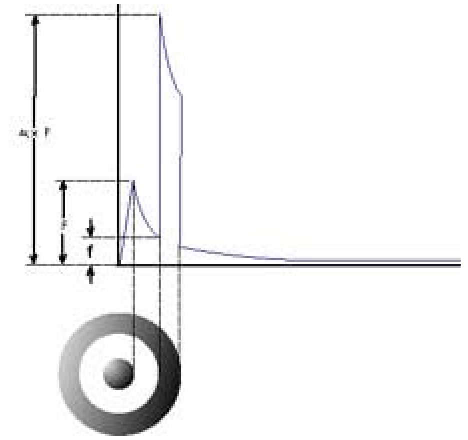
- Same as with a solid conductor, when DC current is passed through a magnetic conductor, the field strength within the conductor is much greater than in nonmagnetic conductor due to the permeability of the magnetic material. The external field strength decreases with distance from the surface of the 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 better method of magnetizing hollow components for inspection of the ID and OD surfaces is with the use of a central conductor. 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

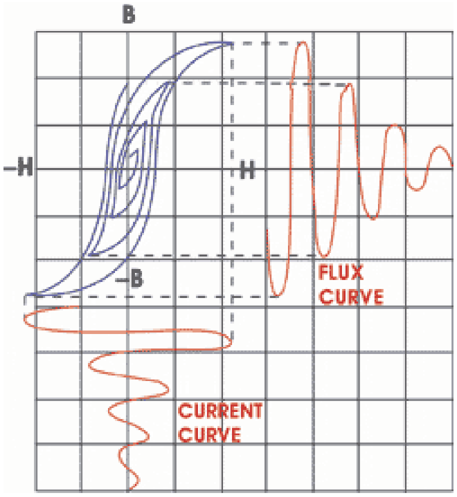
After conducting a magnetic particle inspection, it is usually necessary to demagnetize the component. Remanent magnetic fields can:

- 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 heating the material above its curie temperature (*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 placed with its long axis in an east-west orientation 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 reversing and decreasing magnetic field will return the dipoles to a nearly random orientation throughout the material. This can be accomplished by pulling a component out and away from a coil 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

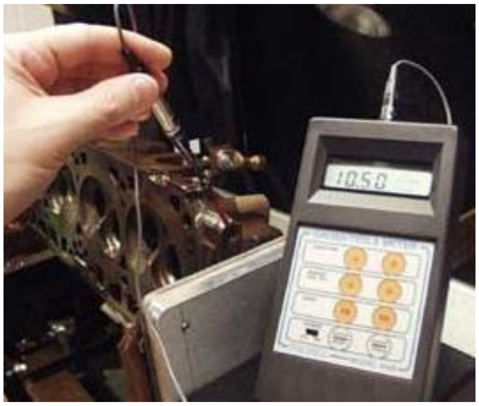
When performing a magnetic particle inspection, it is very important to be able to determine the direction and intensity of the magnetic field. The field intensity must be high enough to cause an indication to form, but not too high to cause nonrelevant indications to mask relevant indications. Also,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

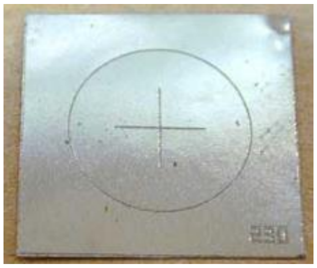
Magnetic Field Indicators

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.

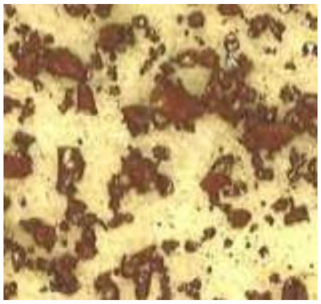
Magnetic Particles

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.

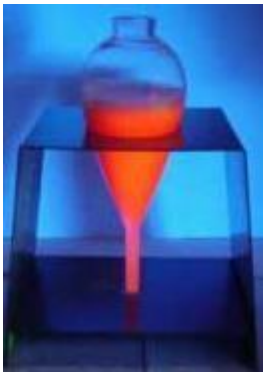
The particle shape is also important. Long, slender particles tend to align themselves along the lines of magnetic force. However, if dry powder consists only of elongated particles, the application process would be less than desirable since long particles lack the ability to flow freely. Therefore, 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 µW/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.

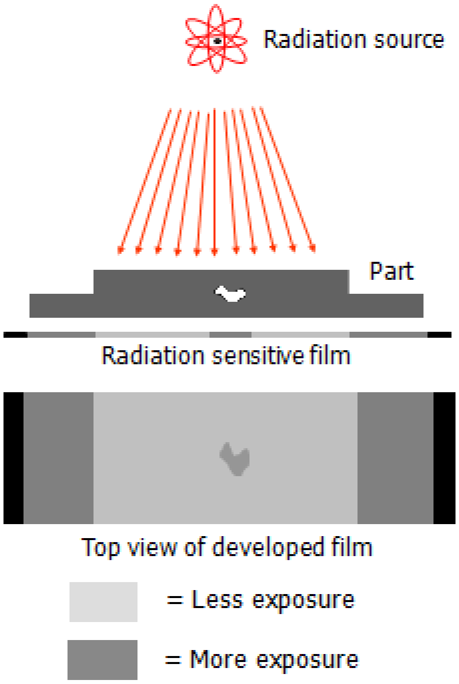
Radiographic Testing

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 (lower *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.

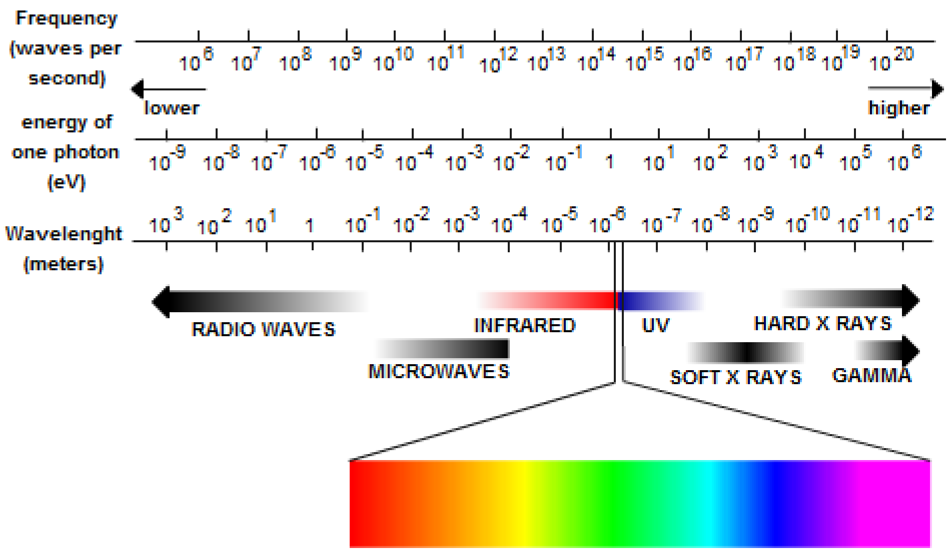
Disadvantages

- 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.

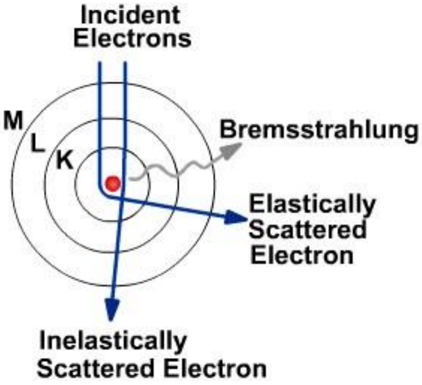
X-Radiation

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.

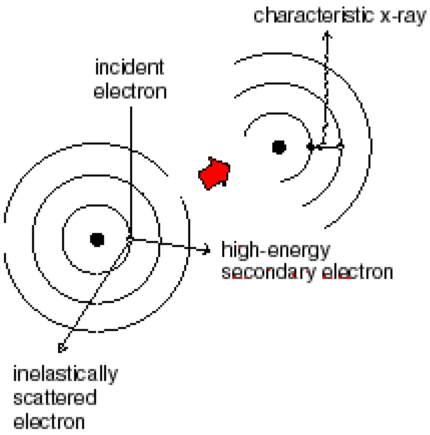
Bremsstrahlung Radiation

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.

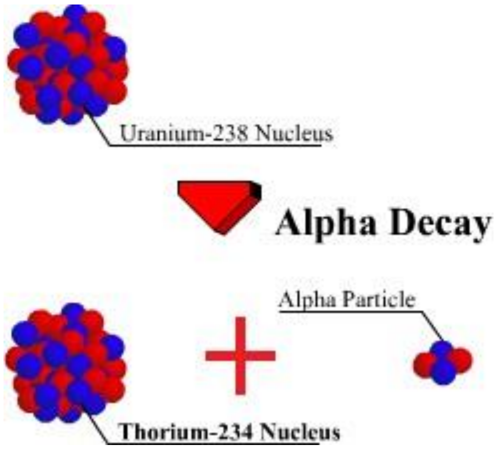
Gamma radiation is the product of radioactive atoms. Depending upon the ratio of neutrons to protons within its nucleus, an isotope of a particular element may be stable or unstable. When the binding energy is not strong enough to hold the nucleus of an atom together, the atom is said to be unstable. 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.

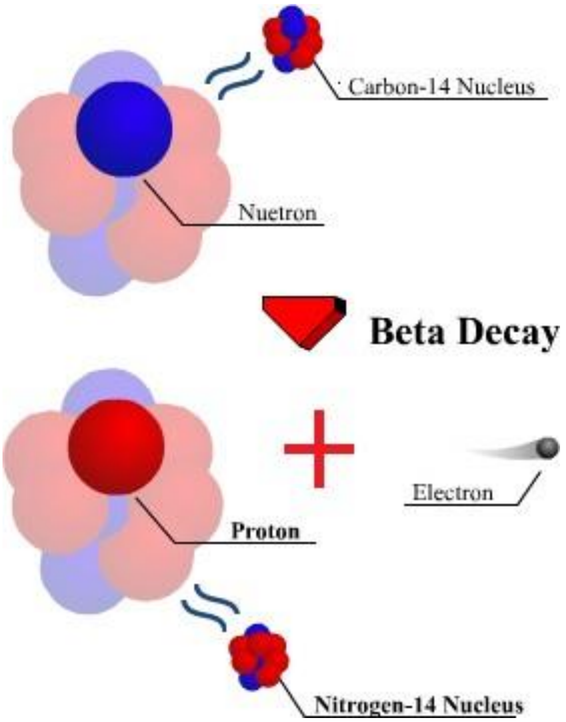
Alpha Particles

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.

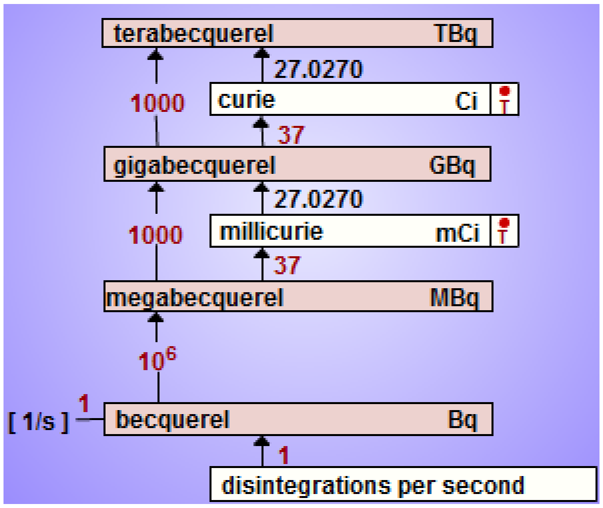


Gamma-rays

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*)

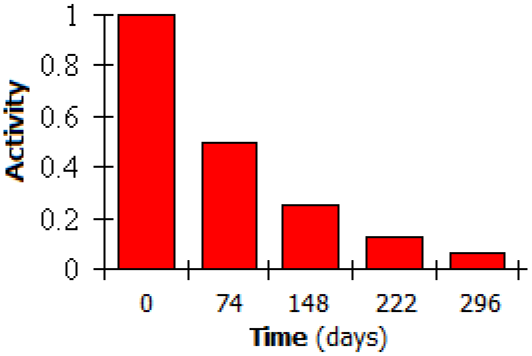
The quantity which expresses the radiation producing potential of a given amount of radioactive material is called "*Activity*". The *Curie* (***Ci***) was originally defined as that amount of any radioactive material that disintegrates at the same rate as one gram of pure radium. The International System (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

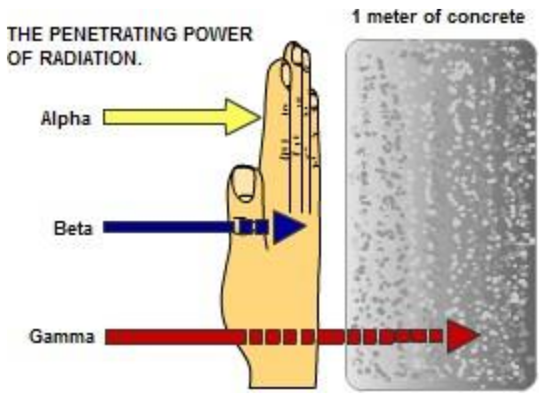
Radiation intensity is the amount of energy passing through a given area that is perpendicular to the direction of radiation travel in a given unit of time. One way to measure the intensity of X-rays or gamma rays is to measure the amount of ionization they cause in air. The amount of ionization in air 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.

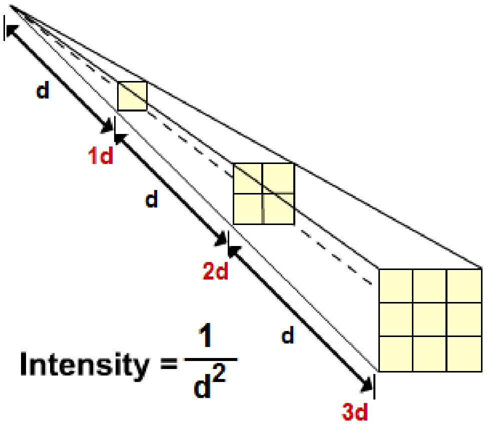
Because of their double charge and relatively slow velocity, alpha particles have a relatively short range in matter (a few centimeters in air and only fractions of a millimeter in tissue). Beta particles have, generally, a greater range.



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.



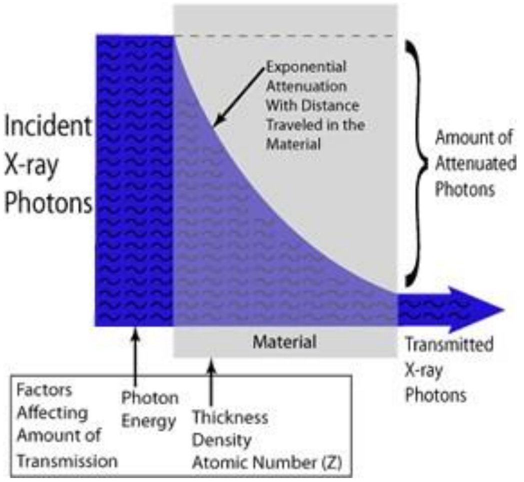
As one of the fields which obey the general inverse square law, the intensity of the radiation received from a point radiation source can be characterized by the diagram above. The relation between intensity and distance according to the inverse square law can be expresses as:

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

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

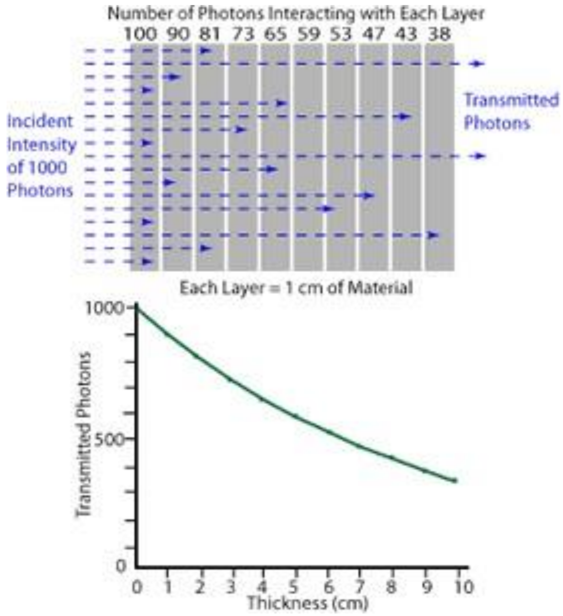
All measures of exposure or dose rate will drop off by the inverse square law. For example, if the received dose of radiation is *100 mR/hr* at *2 cm* from a source, it will be *0.01 mR/hr* at *2 m*.

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
μ : linear attenuation coefficient per unit distance
x : distance traveled through the matter

Linear and Mass Attenuation Coefficients

The "*linear attenuation coefficient*" (μ) 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 μ 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 μ 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 (μ/ρ) is known as the mass attenuation coefficient and has units of *cm²/gm*. The mass attenuation coefficient can simply be converted to a linear attenuation coefficient by multiplying it by the density (ρ) of the material.

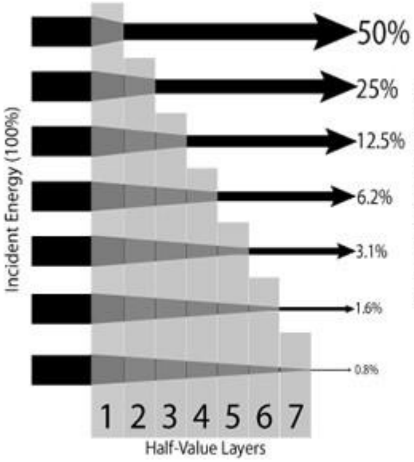
Half-Value Layer

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:

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

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:

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

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*

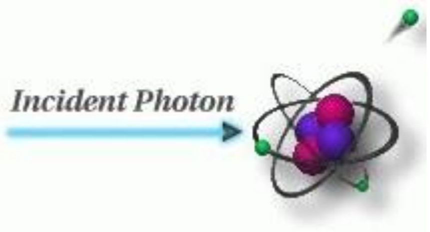
Approximate *HVL* for some materials when radiation is from an X-ray source:

	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*

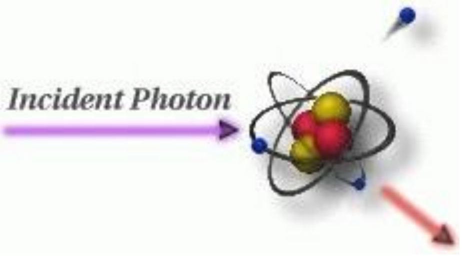
Sources of Attenuation

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.

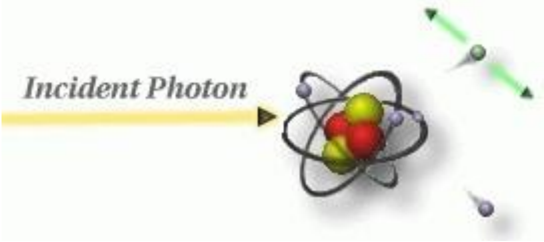
- *Photoelectric (**PE**) absorption* of X-rays occurs when the X-ray photon is absorbed, resulting in the ejection of electrons from the outer shell of the atom, and hence the ionization of the atom. Subsequently, the ionized atom returns to the neutral state with the emission of an X-ray characteristic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

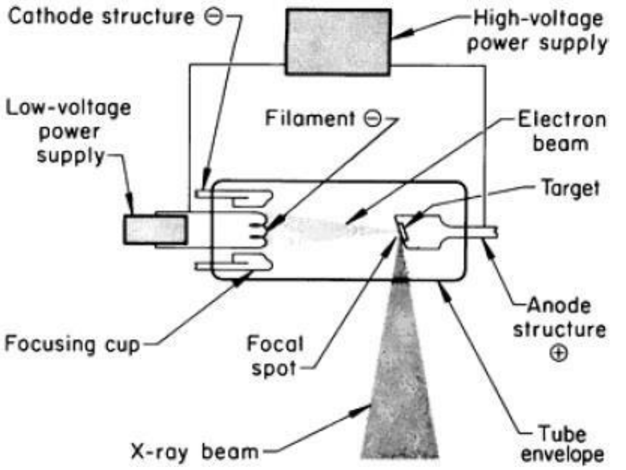


EQUIPMENT & MATERIALS

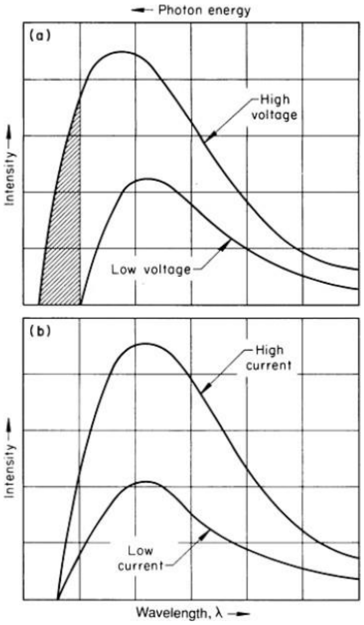
X-ray Generators

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 awarm-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*).

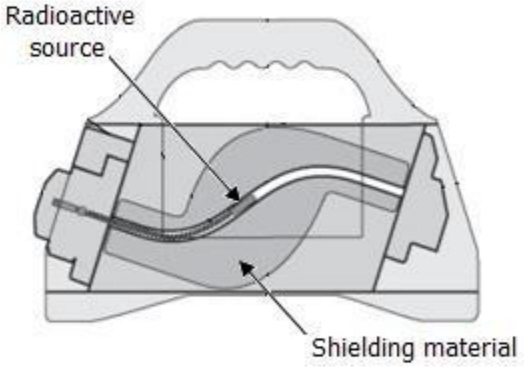
The other important component of an X-ray generating system is the control console. Consoles typically have a keyed lock to prevent unauthorized use of the system. They will have a button to start the generation of X-rays and a button to manually stop the generation of X-rays. The three main adjustable 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

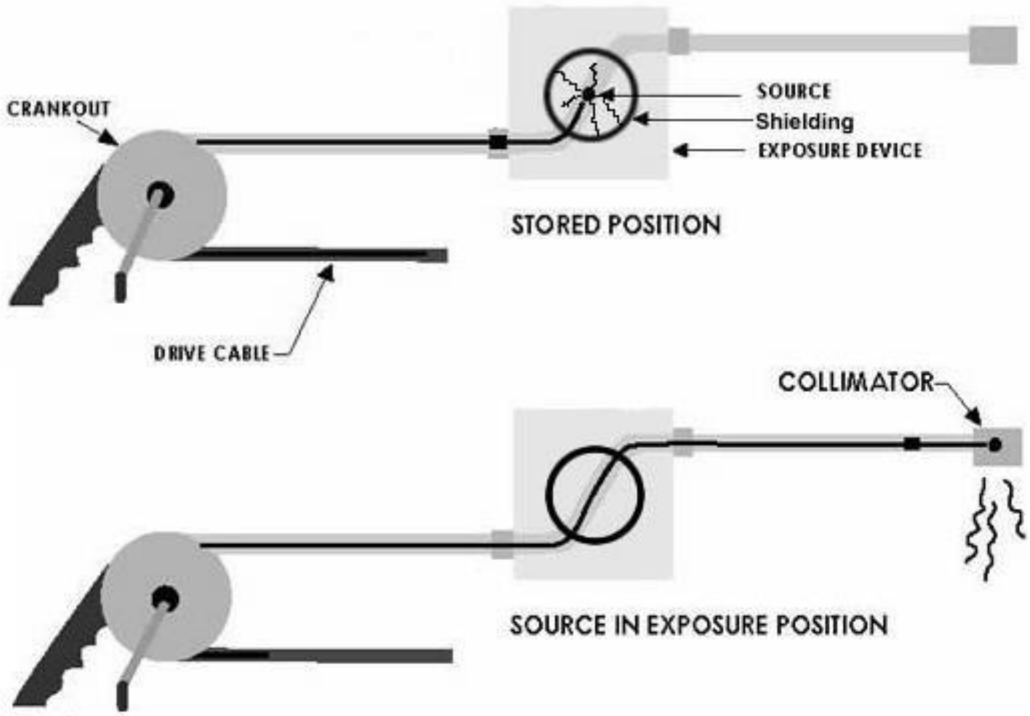
Manmade radioactive sources are produced by introducing an extra neutron to atoms of the source material. As the material gets rid of the neutron, energy is released in the form of gamma rays. Two of the most common industrial gamma-ray sources for industrial radiography are Iridium-192 and Cobalt-60. 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.

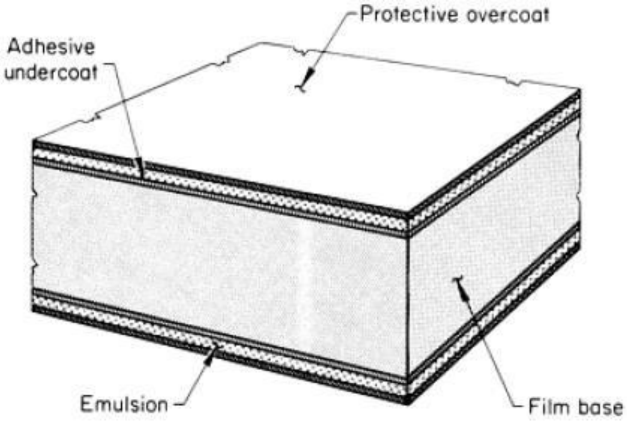


To make a radiographic exposure, a crank-out mechanism and a guide tube are attached to opposite ends of the exposure device. The guide tube often has a collimator (*usually made of tungsten*) at the end to shield the radiation except in the direction necessary to make the exposure. The end of the guide 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

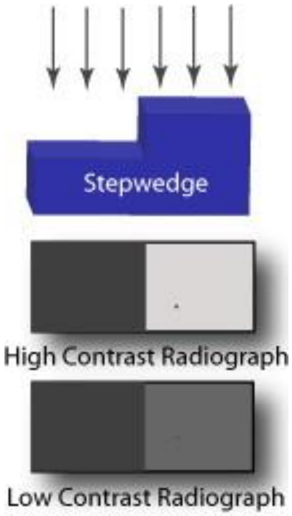
X-ray film should always be handled carefully to avoid physical strains, such as pressure, creasing, buckling, friction, etc. Whenever films are loaded in semi-flexible holders and external clamping devices are used, care should be taken to be sure pressure is uniform. Marks resulting from contact with 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

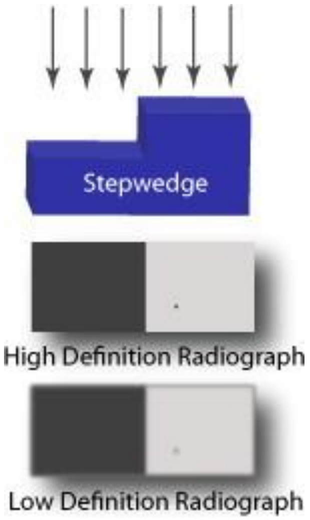
Radiographic Sensitivity

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.

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

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.

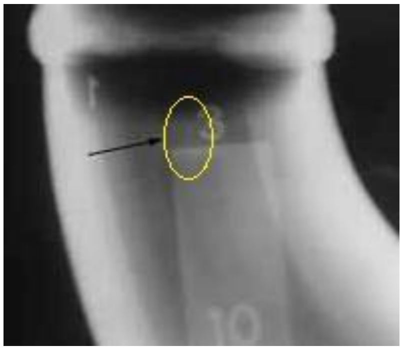
Film density is measured with a "*densitometer*" which simply measures the amount of light transmitted through a piece of film using a photovoltic sensor.

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*).

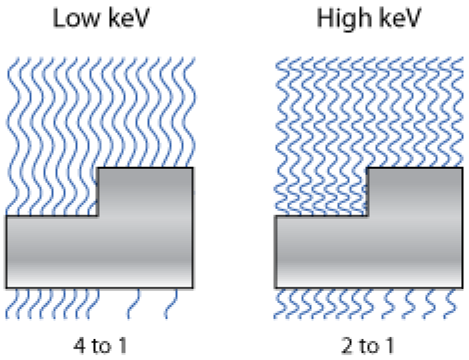
Radiographic Contrast

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.

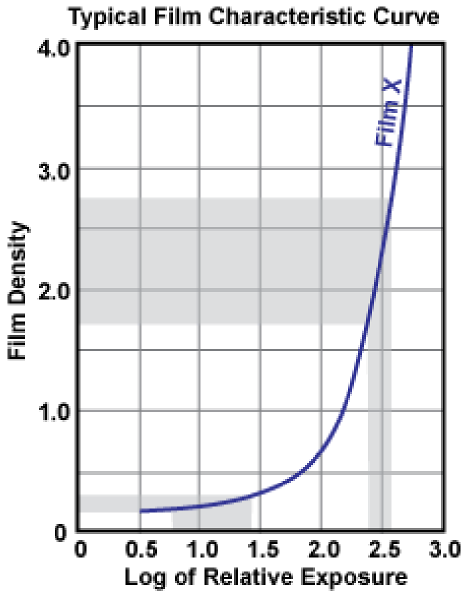


There is a tradeoff, however. Generally, as contrast sensitivity increases, the latitude of the radiograph decreases. Radiographic latitude refers to the range of material thickness that can be imaged. This means that more areas of different thicknesses will be visible in the image. Therefore, the goal 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.

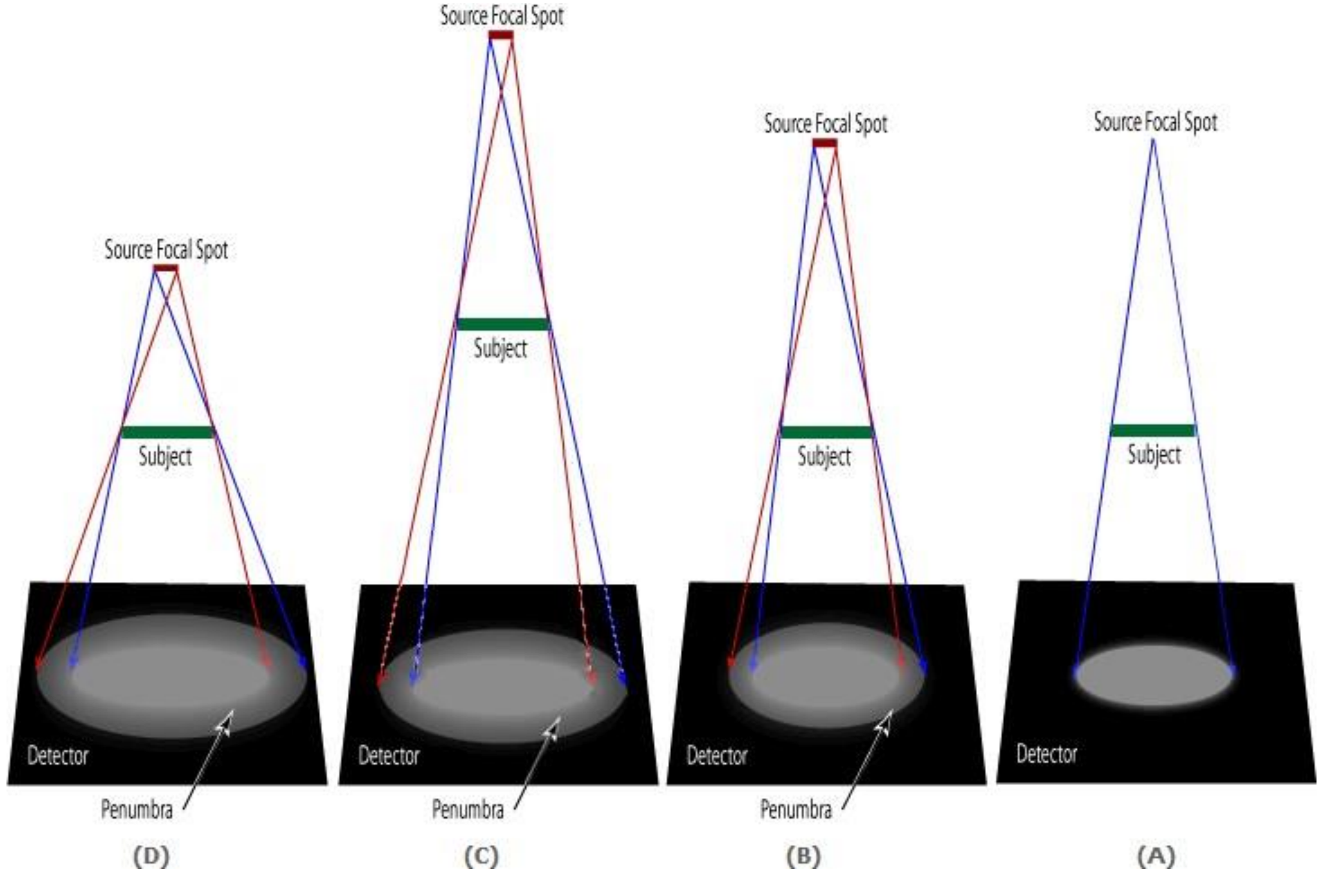
Other type of screens called "fluorescent screens" can alternatively be used where they produce visible light when exposed to radiation and this light further exposes the film and increases density and contrast.

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

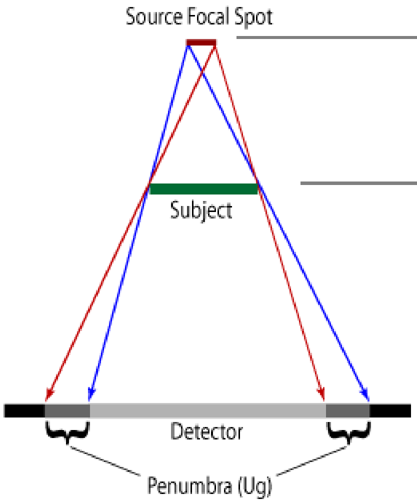
The loss of definition resulting from geometric factors of the radiographic equipment and setup is refered to as "*geometric unsharpness*". It occurs because the radiation does not originate from a single point but rather over an area. The three factors controlling unsharpness are source size, source 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:

$$\boxed{U_g = d_s \frac{b}{\,}}$$

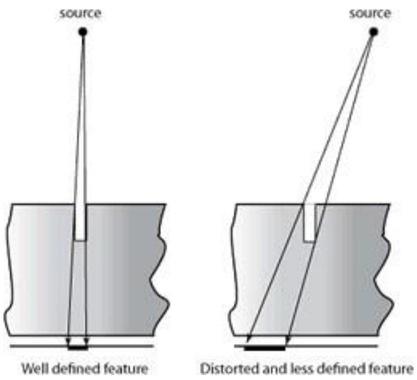
Where;

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

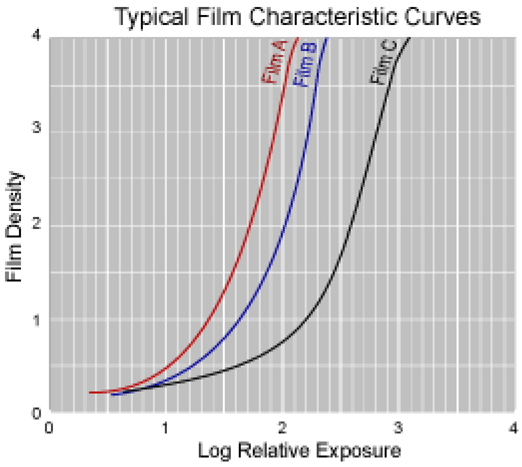
The last set of factors concern the film and the use of fluorescent screens. A <u>fine grain</u> film is capable of producing an image with a <u>higher level of definition</u> than is a coarse grain film. Wavelength of the radiation will influence apparent graininess. As the wavelength shortens and penetration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

The use of <u>fluorescent screens</u> also results in <u>lower definition</u>. 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 <u>produce screen mottle on radiographs</u>. Screen mottle is associated with the statistical variation in the numbers of photons that interact with the screen from one area to the next.

<u>Film Characteristic Curves</u>

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 <u>log units</u> 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*.

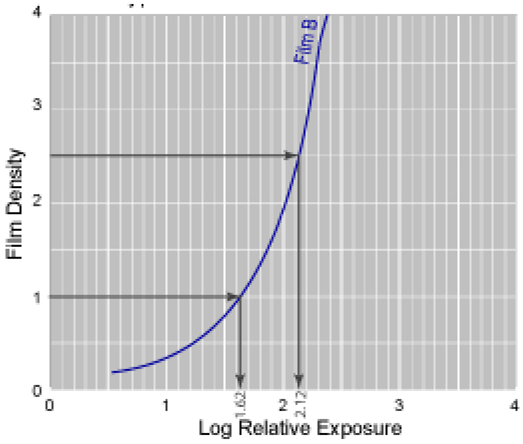
The location of the characteristic curves of different films along the *x*-axis relates to the speed of the film. The farther to the right that a curve is on the chart, the slower the film speed (*Film A has the highest speed while film C has the lowest speed*). The shape of the characteristic curve 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?

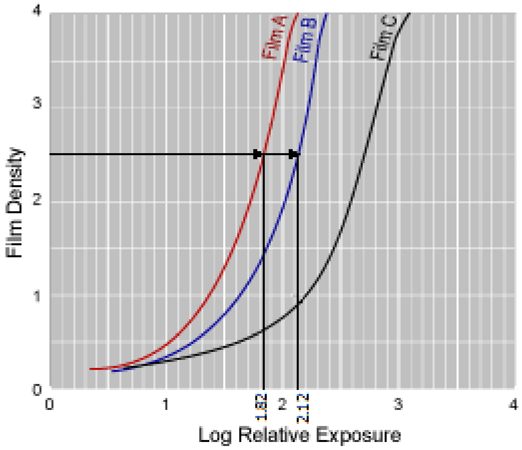
From the graph, the log of the relative exposure of a density of *1.0* is *1.62* and the log of the relative exposure when the density of the film is *2.5* is *2.12*.
The difference between the two values is *0.5*.
$10^{0.5} = 3.16$
Therefore, the exposure used to produce the initial radiograph with 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:

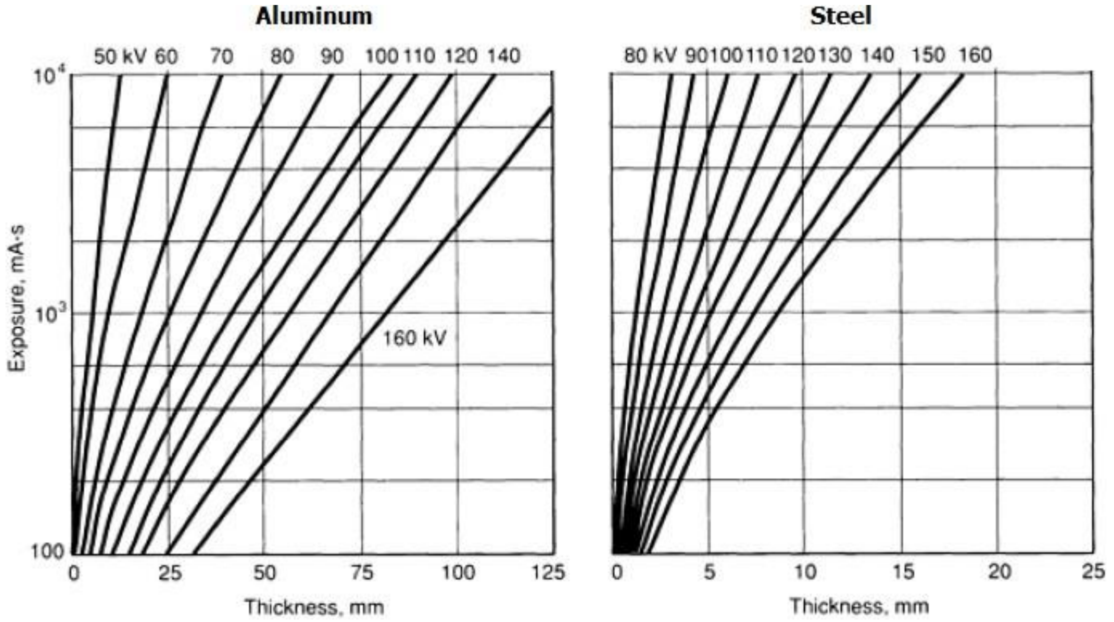
- The spectrum of radiation produced by the X-ray generator.
- The voltage potential used to generate the X-rays (*kV*).
- The amperage used to generate the X-rays (*mA*).
- The exposure time.
- The distance between the radiation source and the film.
- The material of the component being radiographed.
- 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.

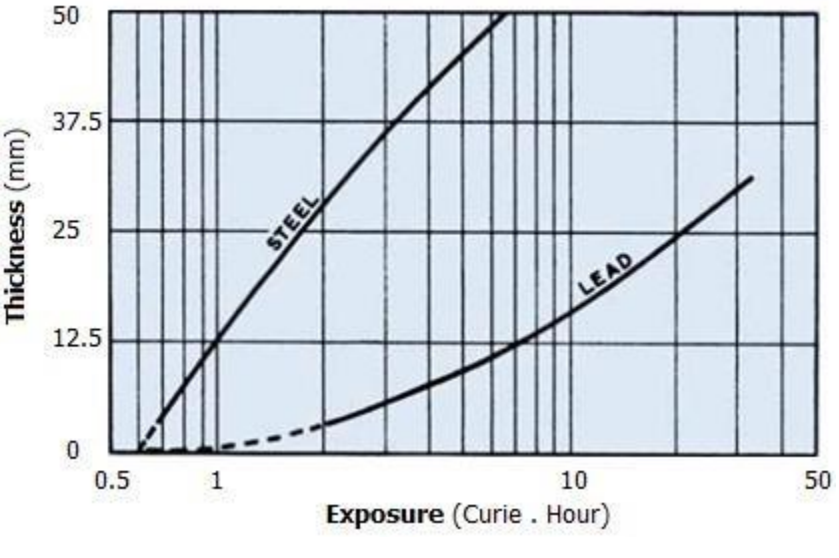
However, it is possible to calculate the density of a radiograph to an acceptable degree of accuracy when the spectrum of an X-ray generator has been characterized. The calculation cannot completely account for scattering but, otherwise, the relationship between many of the variables and their effect 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, *Il-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.

<u>Example 1:</u>

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*?

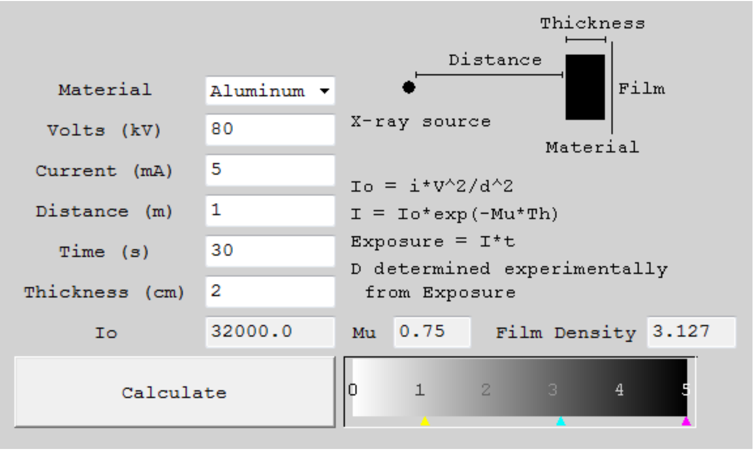
Answer: *190 s*

<u>Example 2:</u>

A *12.5 mm* thick Steel plate is to be radiographed without screens using Ir-192 source at 4*55 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.



Material	Aluminum
Volts (kV)	80
Current (mA)	5
Distance (m)	1
Time (s)	30
Thickness (cm)	2
Io	32000.0
Mu	0.75
Film Density	3.127

```
Io = i*V^2/d^2
I = Io*exp(-Mu*Th)
Exposure = I*t
D determined experimentally
  from Exposure
```

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.

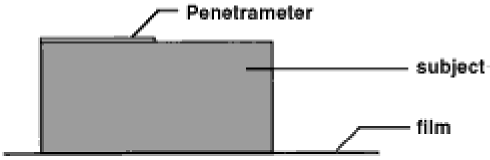
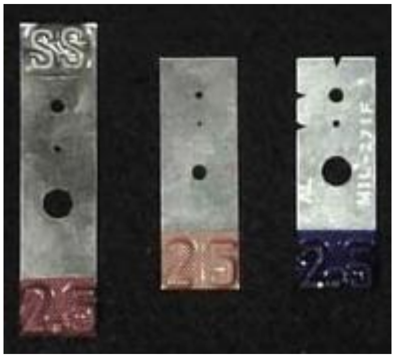


Image quality indicators take many shapes and forms due to the various codes or standards that invoke their use. The two most commonly used IQI types are: the hole-type and the wire IQIs. IQIs come in a variety of material types so that one with radiation absorption characteristics similar to the material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

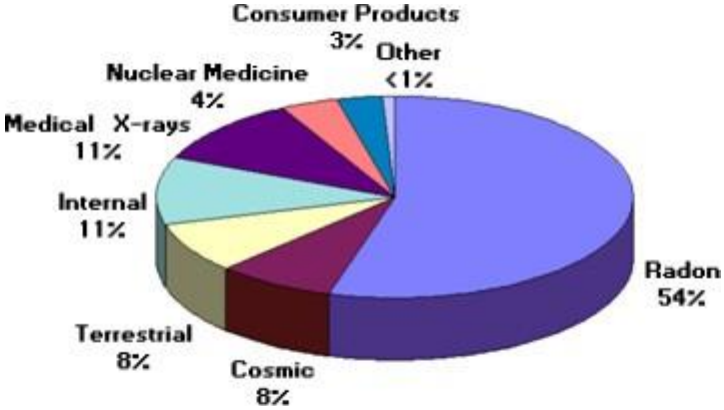
- *Type of radiation involved*. All kinds of ionizing radiation can produce health effects. The main difference in the ability of alpha and beta particles and gamma and X-rays to cause health effects is the amount of energy they have. Their energy determines how far they can penetrate into tissue and 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.

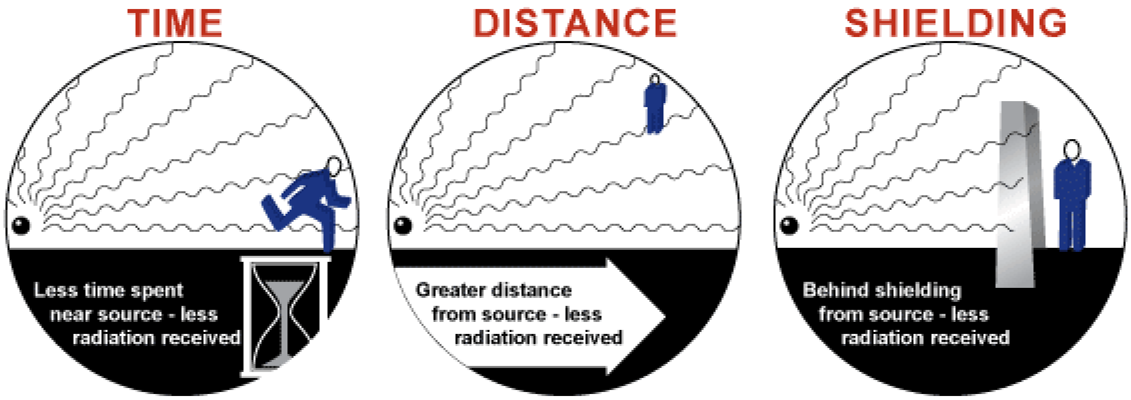
Type of Radiation	Rad	Q Factor	Rem
X-Ray	1	1	1
Gamma Ray	1	1	1
Beta Particles	1	1	1
Thermal Neutrons	1	5	5
Fast Neutrons	1	10	10
Alpha Particles	1	20	20

***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:

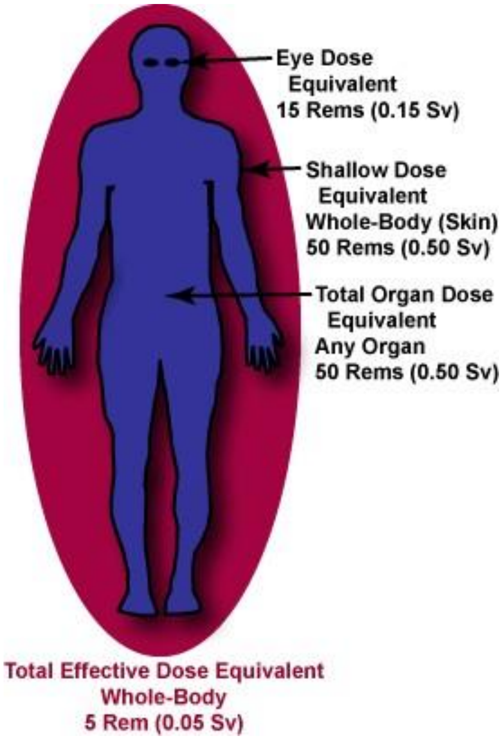
Regulatory Limits for Occupational Exposure

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.

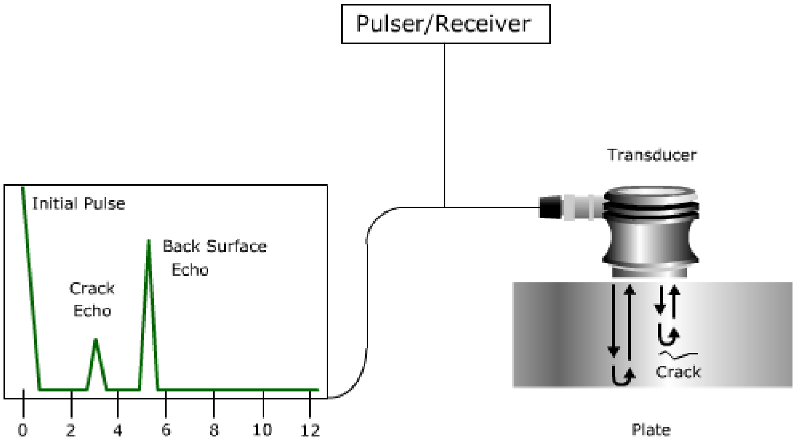
Ultrasonic Testing

Ultrasonic Testing (UT) uses high frequency sound waves (*typically in the range between 0.5 and 15 MHz*) to conduct examinations and make measurements. Besides its wide use in engineering applications (*such as flaw detection/evaluation, dimensional measurements, material characterization, etc.*), ultrasonics are also used in the medical field (*such as sonography, therapeutic ultrasound, etc.*).

In general, ultrasonic testing is based on the capture and quantification of either the reflected waves (*pulse-echo*) or the transmitted waves (*through-transmission*). Each of the two types is used in certain applications, but generally, pulse echo systems are more useful since they require one-sided access to the object being inspected.

Basic Principles

A typical pulse-echo UT inspection system consists of several functional units, such as the pulser/receiver, transducer, and a display device. A pulser/receiver is an electronic device that can produce high voltage electrical pulses. Driven by the pulser, the transducer generates high frequency ultrasonic energy. The sound energy is introduced and propagates through the materials in the form of waves. When there is a discontinuity (*such as a crack*) in the wave path, part of the energy will be reflected back from the flaw surface. The reflected wave signal is transformed into an electrical signal by the transducer and is displayed on a screen. Knowing the velocity of the waves, travel time can be directly related to the distance that the signal traveled. From the signal, information about the reflector location, size, orientation and other features can sometimes be gained.



Advantages and Disadvantages

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

Advantages

- It is sensitive to both surface and subsurface discontinuities.
- The depth of penetration for flaw detection or measurement is superior to other NDT methods.
- Only single-sided access is needed when the pulse-echo technique is used.
- It is highly accurate in determining the reflector position and estimating its size and shape.
- Minimal part preparation is required.
- It provides instantaneous results.
- Detailed images can be produced with automated systems.
- It is nonhazardous to operators or nearby personnel and does not affect the material being tested.
- It has other uses, such as thickness measurement, in addition to flaw detection.
- Its equipment can be highly portable or highly automated.

Disadvantages

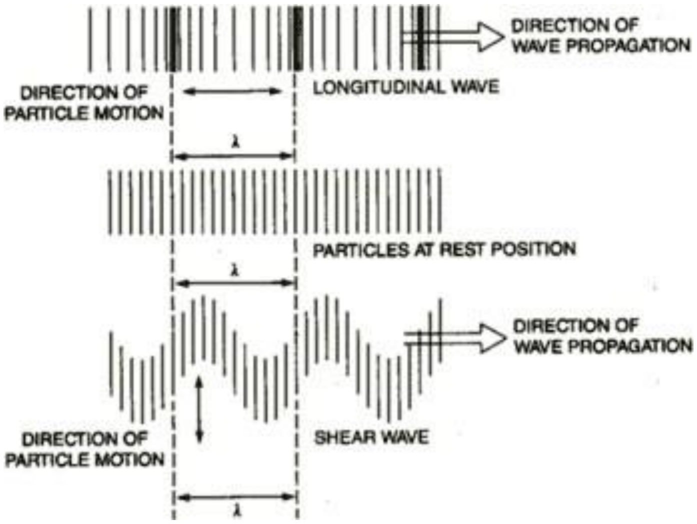
- Surface must be accessible to transmit ultrasound.
- Skill and training is more extensive than with some other methods.
- It normally requires a coupling medium to promote the transfer of sound energy into the test specimen.
- Materials that are rough, irregular in shape, very small, exceptionally thin or not homogeneous are difficult to inspect.
- Cast iron and other coarse grained materials are difficult to inspect due to low sound transmission and high signal noise.
- Linear defects oriented parallel to the sound beam may go undetected.
- Reference standards are required for both equipment calibration and the characterization of flaws.

PHYSICS OF ULTRASOUND

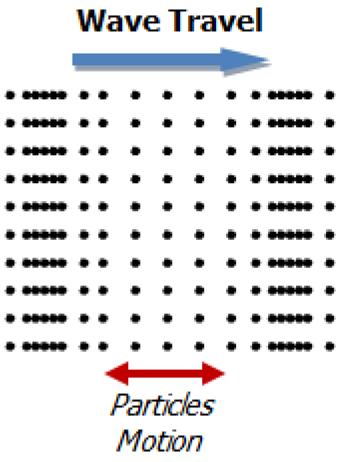
Wave Propagation

Ultrasonic testing is based on the vibration in materials which is generally referred to as acoustics. All material substances are comprised of atoms, which may be forced into vibrational motion about their equilibrium positions. Many different patterns of vibrational motion exist at the atomic level; however, most are irrelevant to acoustics and ultrasonic testing. Acoustics is focused on particles that contain many atoms that move in harmony to produce a mechanical wave. When a material is not stressed in tension or compression beyond its elastic limit, its individual particles perform elastic oscillations. When the particles of a medium are displaced from their equilibrium positions, internal restoration forces arise. These elastic restoring forces between particles, combined with inertia of the particles, lead to the oscillatory motions of the medium.

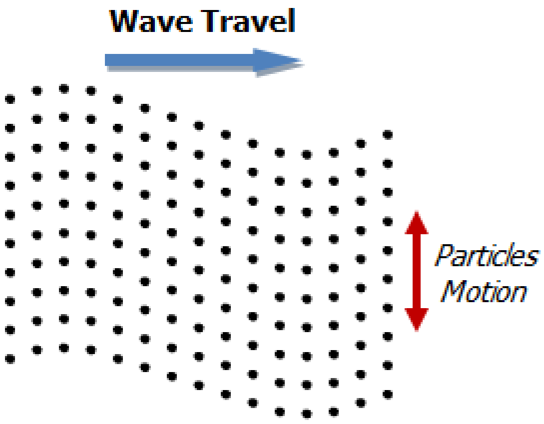
In solids, sound waves can propagate in four principal modes that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. Longitudinal and shear waves are the two modes of propagation most widely used in ultrasonic testing. The particle movement responsible for the propagation of longitudinal and shear waves is illustrated in the figure.



- In *longitudinal waves*, the oscillations occur in the longitudinal direction or the direction of wave propagation. Since compression and expansion forces are active in these waves, they are also called pressure or compression waves. They are also sometimes called density waves because material density fluctuates as the wave moves. Compression waves can be generated in gases, liquids, as well as solids because the energy travels through the atomic structure by a series of compressions and expansion movements.



- In the *transverse or shear waves*, particles oscillate at a right angle or transverse to the direction of propagation. Shear waves require an acoustically solid material for effective propagation, and therefore, are not effectively propagated in materials such as liquids or gasses. Shear waves are relatively weak when compared to longitudinal waves. In fact, shear waves are usually generated in materials using some of the energy from longitudinal waves.



Modes of Sound Wave Propagation

In air, sound travels by the compression and rarefaction of air molecules in the direction of travel. However, in solids, molecules can support vibrations in other directions. Hence, a number of different types of sound waves are possible. Waves can be characterized by oscillatory patterns that are capable of maintaining their shape and propagating in a stable manner. The propagation of waves is often described in terms of what are called "*wave modes*".

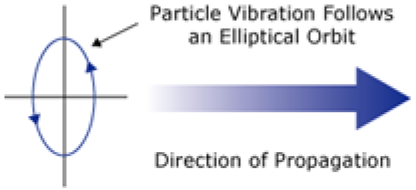
As mentioned previously, longitudinal and transverse (shear) waves are most often used in ultrasonic inspection. However, at surfaces and interfaces, various types of elliptical or complex vibrations of the particles make other waves possible. Some of these wave modes such as Rayleigh and Lamb waves are also useful for ultrasonic inspection.

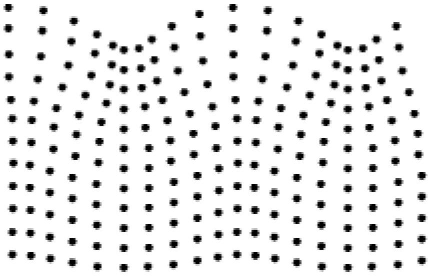
Though there are many different modes of wave propagation, the table summarizes the four types of waves that are used in NDT.

Wave Type	**Particle Vibration**
Longitudinal (Compression)	Parallel to wave direction
Transverse (Shear)	Perpendicular to wave direction
Surface - Rayleigh	Elliptical orbit - symmetrical mode
Plate Wave - Lamb	Component perpendicular to surface

Since longitudinal and transverse waves were discussed previously, surface and plate waves are introduced here.

- *Surface (or Rayleigh) waves* travel at the surface of a relatively thick solid material penetrating to a depth of one wavelength. A surface wave is a combination of both a longitudinal and transverse motion which results in an elliptical motion as shown in the image. The major axis of the ellipse is perpendicular to the surface of the solid. As the depth of an individual atom from the surface increases, the width of its elliptical motion decreases. Surface waves are generated when a longitudinal wave intersects a surface slightly larger than the second critical angle and they travel at a velocity between .87 and .95 of a shear wave. Rayleigh waves are useful because they are very sensitive to surface defects (*and other surface features*) and they follow the surface around curves. Because of this, Rayleigh waves can be used to inspect areas that other waves might have difficulty reaching.

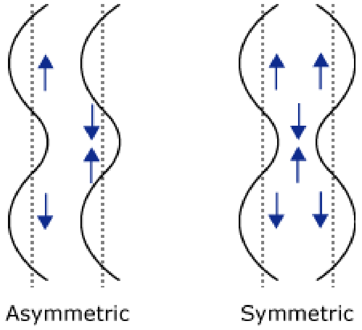




- *Plate (or Lamb) waves* are similar to surface waves except they can only be generated in materials a few wavelengths thick (*thin plates*). Lamb waves are complex vibrational waves that propagate parallel to the test surface throughout the thickness of the material. They are influenced a great deal by the test wave frequency and material thickness. Lamb waves are generated when a wave hits a surface at an incident angle such that the parallel component of the velocity of the wave (in the source) is equal to the velocity of the wave in the test material. Lamb waves will travel several meters in steel and so are useful to scan plate, wire, and tubes.
    - With Lamb waves, a number of modes of particle vibration are possible, but the two most common are symmetrical and asymmetrical. The complex motion of the particles is similar to the elliptical orbits for surface waves.

      Symmetrical Lamb waves move in a symmetrical fashion about the median plane of the plate. This is sometimes called the "*extensional mode*" because the wave is stretching and compressing the plate in the wave motion direction.

      The asymmetrical Lamb wave mode is often called the "*flexural mode*" because a large portion of the motion is in a normal direction to the plate, and a little motion occurs in the direction parallel to the plate. In this mode, the body of the plate bends as the two surfaces move in the same direction.



Properties of Acoustic Waves

Among the properties of waves propagating in isotropic solid materials are wavelength, frequency, and velocity. The wavelength is directly proportional to the velocity of the wave and inversely proportional to the frequency of the wave. This relationship is shown by the following equation:

$$\boxed{\lambda = \frac{V}{\mathbf{f}}}$$

Where;

λ : wavelength (*m*)
V : velocity (*m/s*)
f : frequency (*Hz*)

The velocity of sound waves in a certain medium is fixed where it is a characteristic of that medium. As can be noted from the equation, an increase in frequency will result in a decrease in wavelength. For instance, the velocity of longitudinal waves in steel is *5850 m/s* and that results in a wavelength of *5.85 mm* when the frequency is *1 MHz*.

Wavelength and Defect Detection

In ultrasonic testing, the inspector must make a decision about the frequency of the transducer that will be used in order to control the wavelength. The wavelength of the ultrasound used has a significant effect on the probability of detecting a discontinuity. A general rule of thumb is that a discontinuity must be larger than one-half the wavelength to stand a reasonable chance of being detected.

Sensitivity and ***resolution*** are two terms that are often used in ultrasonic inspection to describe a technique's ability to locate flaws. *Sensitivity* is the ability to locate small discontinuities. Sensitivity generally increases with higher frequency (*shorter wavelengths*). *Resolution* is the ability of the system to locate discontinuities that are close together within the material or located near the part surface. Resolution also generally increases as the frequency increases.

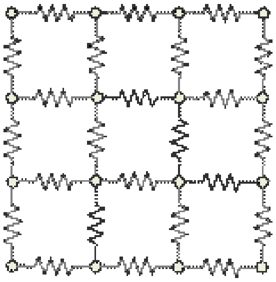
The wave frequency can also affect the capability of an inspection in adverse ways. Therefore, selecting the optimal inspection frequency often involves maintaining a balance between the favorable and unfavorable results of the selection. Before selecting an inspection frequency, the material's grain structure and thickness, and the discontinuity's type, size, and probable location should be considered. As frequency increases, sound tends to scatter from large or course grain structure and from small imperfections within a material. Cast materials often have coarse grains and thus require lower frequencies to be used for evaluations of these products. Wrought and forged products with directional and refined grain structure can usually be inspected with higher frequency transducers.

Since more things in a material are likely to scatter a portion of the sound energy at higher frequencies, the ***penetration depth*** (*the maximum depth in a material that flaws can be located*) is also reduced. Frequency also has an effect on the shape of the ultrasonic beam. Beam spread, or the divergence of the beam from the center axis of the transducer, and how it is affected by frequency will be discussed later.

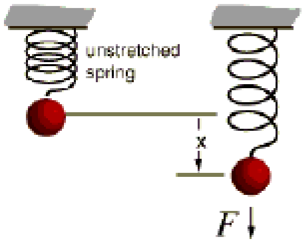
It should be mentioned, so as not to be misleading, that a number of other variables will also affect the ability of ultrasound to locate defects. These include the pulse length, type and voltage applied to the crystal, properties of the crystal, backing material, transducer diameter, and the receiver circuitry of the instrument. These are discussed in more detail in a later section.

Sound Propagation in Elastic Materials

It was mentioned previously that sound waves propagate due to the vibrations or oscillatory motions of particles within a material. An ultrasonic wave may be visualized as an infinite number of oscillating masses or particles connected by means of elastic springs. Each individual particle is influenced by the motion of its nearest neighbor and both inertial and elastic restoring forces act upon each particle.



A mass on a spring has a single resonant frequency (*natural frequency*) determined by its spring constant ***k*** and its mass ***m***. Within the elastic limit of any material, there is a linear relationship between the displacement of a particle and the force attempting to restore the particle to its equilibrium position. This linear dependency is described by *Hooke's Law*. In terms of the spring model, the relation between force and displacement is written as ***F = k x***.



The Speed of Sound

Hooke's Law, when used along with Newton's Second Law, can explain a few things about the speed of sound. The speed of sound within a material is a function of the properties of the material and is independent of the amplitude of the sound wave. Newton's Second Law says that the force applied to a particle will be balanced by the particle's mass and the acceleration of the particle. Mathematically, Newton's Second Law is written as $\boldsymbol{F = m\,a}$. Hooke's Law then says that this force will be balanced by a force in the opposite direction that is dependent on the amount of displacement and the spring constant. Therefore, since the applied force and the restoring force are equal, $\boldsymbol{m\,a = k\,x}$ can be written.

Since the mass $\boldsymbol{m}$ and the spring constant $\boldsymbol{k}$ are constants for any given material, it can be seen that the acceleration $\boldsymbol{a}$ and the displacement $\boldsymbol{x}$ are the only variables. It can also be seen that they are directly proportional. For instance, if the displacement of the particle increases, so does its acceleration. It turns out that the time that it takes a particle to move and return to its equilibrium position is independent of the force applied. So, within a given material, sound always travels at the same speed no matter how much force is applied when other variables, such as temperature, are held constant.

Material Properties Affecting the Speed of Sound

Of course, sound does travel at different speeds in different materials. This is because the mass of the atomic particles and the spring constants are different for different materials. The mass of the particles is related to the density of the material, and the spring constant is related to the elastic constants of a material. The general relationship between the speed of sound in a solid and its density and elastic constants is given by the following equation:

$$V = \sqrt{\frac{C_{\mathrm{ij}}}{\rho}}$$

Where;

V : speed of sound (*m/s*)
C_{ij} : elastic constant “in a given direction” (N/m^2)
ρ : density (kg/m^3)

This equation may take a number of different forms depending on the type of wave (*longitudinal or shear*) and which of the elastic constants that are used. It must also be mentioned that the subscript “ij” attached to “C” in the above equation is used to indicate the directionality of the elastic constants with respect to the wave type and direction of wave travel. In isotropic materials, the elastic constants are the same for all directions within the material. However, most materials are anisotropic and the elastic constants differ with each direction. For example, in a piece of rolled aluminum plate, the grains are elongated in one direction and compressed in the others and the elastic constants for the longitudinal direction differs slightly from those for the transverse or short transverse directions.

For longitudinal waves, the speed of sound in a solid material can be found as:

$$\boxed{V_L = \sqrt{\frac{E(1-u)}{\rho(1+u)(1-2u)}}}$$

Where;

V_L : speed of sound for longitudinal waves (*m/s*)
E : Young's modulus (*N/m*^{2})
u : Poisson's ratio

While for shear (*transverse*) waves, the speed of sound is found as:

$$\boxed{V_T = \sqrt{\frac{G}{\rho}}}$$

Where;

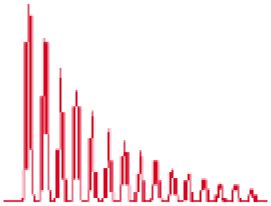
V_T : speed of sound for shear waves (*m/s*)
G : Shear modulus of elasticity (*N/m*^{2}); $G = E/2(1+u)$

From the above equations, it can be found that longitudinal waves travel faster than shear waves (*longitudinal waves are approximately twice as fast as shear waves*). The table below gives examples of the compressional and shear sound velocities in some metals.

Material	**Compressional velocity** $V_L\ (m/s)$	**Shear velocity** $V_T\ (m/s)$
Aluminum	6320	3130
Steel (1020)	5890	3240
Cast iron	4800	2400
Copper	4660	2330
Titanium	6070	3310

Attenuation of Sound Waves

When sound travels through a medium, its intensity diminishes with distance. In idealized materials, sound pressure (*signal amplitude*) is reduced due to the spreading of the wave. In natural materials, however, the sound amplitude is further weakened due to the scattering and absorption. Scattering is the reflection of the sound in directions other than its original direction of propagation. Absorption is the conversion of the sound energy to other forms of energy. The combined effect of scattering and absorption is called attenuation. Attenuation is generally proportional to the square of sound frequency.



The amplitude change of a decaying plane wave can be expressed as:

$$\boxed{A = A_0 e^{-\alpha z}}$$

Where;

A_0 : initial (*unattenuated*) amplitude
α : attenuation coefficient (*Np/m*)
z : traveled distance (*m*)

Np (Neper) is a logarithmic dimensionless *quantity and it can be converted to Decibels by dividing it by 0.1151. Decibel is a more common unit when relating the amplitudes of two signals.*

The ***Decibel*** *(dB) is a logarithmic unit that describes a ratio of two measurements. The difference between two measurements X₁ and X₂ is described in decibels as:*

$$\Delta\ (dB) = 10\ \log\frac{2}{1}$$

The intensity of sound waves (I) is quantified by measuring the variation in sound pressure using a transducer, and then the pressure is transferred to a voltage signal. Since the intensity of sound waves is proportional to the square of the pressure amplitude, the ratio of sound intensity in decibels can be expressed as:

$$\boxed{\Delta I\ (dB)} = 10\ \log\frac{I_2}{I_1} = 10\ \log\frac{P_2{}^2}{P_1{}^2} = 20\ \log\frac{P_2}{P_1} = \boxed{20\ \log\frac{V_2}{V_1}}$$

where;

ΔI*: the change in sound intensity between two measurements*
V_1 & V_2 *: are the two different transducer output voltages (or readings)*

Use of dB units allows ratios of various sizes to be described using easy to work with numbers.

Ratio between Measurement 1 and 2	Equation	dB
1/2	dB = 20 log (1/2)	- 6 dB
1	dB = 20 log (1)	0 dB
2	dB = 20 log (2)	6 dB
10	dB = 20 log (10)	20 dB
100	dB = 20 log (100)	40 dB

Attenuation can be determined by evaluating the multiple back-wall reflections seen in a typical A-scan display (*like the one shown in the image in the previous page*). The number of decibels between two adjacent signals is measured and this value is divided by the time interval between them. This calculation produces an attenuation coefficient in decibels per unit time. Then knowing the velocity of sound it can be converted to decibels per unit length.

Acoustic Impedance

Sound travels through materials under the influence of sound pressure. Because molecules or atoms of a solid are bound elastically to one another, the excess pressure results in a wave propagating through the solid.

The *acoustic impedance* (Z) of a material is defined as the product of its density (ρ) and the velocity of sound in that material (V).

$$\boxed{Z = \rho V}$$

Where;

Z : acoustic impedance (*kg/m²s*) or (*N s/m³*)
ρ : density (*kg/m³*)
V : sound velocity (*m/s*)

The table gives examples of the acoustic impedances for some materials:

	Aluminum	**Copper**	**Steel**	**Titanium**	**Water** (20°C)	**Air** (20°C)
Acou. Imp. (*kg/m²s*)	17.1×10^6	41.6×10^6	46.1×10^6	28×10^6	1.48×10^6	413

Acoustic impedance is important in:

- The determination of acoustic transmission and reflection at the boundary of two materials having different acoustic impedances.
- The design of ultrasonic transducers.
- Assessing absorption of sound in a medium.

Reflection and Transmission Coefficients

Ultrasonic waves are reflected at boundaries where there is a difference in acoustic impedances (Z) of the materials on each side of the boundary. This difference in Z is commonly referred to as the impedance mismatch. The greater the impedance mismatch, the greater the percentage of energy that will be reflected at the interface or boundary between one medium and another.

The fraction of the incident wave intensity that is reflected can be derived based on the fact that particle velocity and local particle pressures must be continuous across the boundary. When the acoustic impedances of the materials on both sides of the boundary are known, the fraction of the incident wave intensity that is reflected (*the reflection coefficient*) can be calculated as:

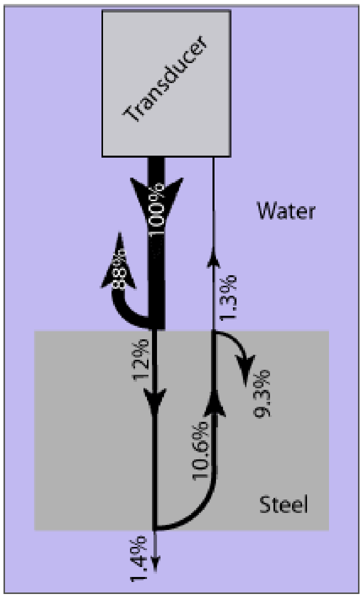
$$\boxed{R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2}$$

Multiplying the reflection coefficient by 100 yields the amount of energy reflected as a percentage of the original energy.

Where Z_2 & Z_1 are the acoustic impedances of the two materials at the interface.

Since the amount of reflected energy plus the transmitted energy must equal the total amount of incident energy, the "*transmission coefficient*" is calculated by simply subtracting the reflection coefficient from one ($T = 1 - R$).

Taking for example a water steel interface and calculating the reflection and transmission coefficients (*using the acoustic impedance information given in the previous table*), we get R= 0.88 and T= 0.12. This means that the amount of energy transmitted into the second material is only 12% while 88% is reflected back at the interface. If we convert the amounts of reflection and transmission to decibels, we find that to be *-1.1 dB* and *-18.4 dB* respectively. The negative sign indicates that individually, the amount of reflected and transmitted energy is smaller than the incident energy.



If reflection and transmission at interfaces is followed through the component, only a small percentage of the original energy makes it back to the transducer, even when loss by attenuation is ignored. For example, consider an immersion inspection of a steel block. The sound energy leaves the transducer, travels through the water, encounters the front surface of the steel, encounters the back surface of the steel and reflects back through the front surface on its way back to the transducer. At the water steel interface (front surface), 12% of the energy is transmitted. At the back surface, 88% of the 12% that made it through the front surface is reflected. This is 10.6% of the intensity of the initial incident wave. As the wave exits the part back through the front surface, only 12% of 10.6 or 1.3% of the original energy is transmitted back to the transducer.

Note that in such calculation the attenuation of the signal as it travels through the material is not considered. Should it be considered, the amount of signal received back by the transducer would be even smaller.

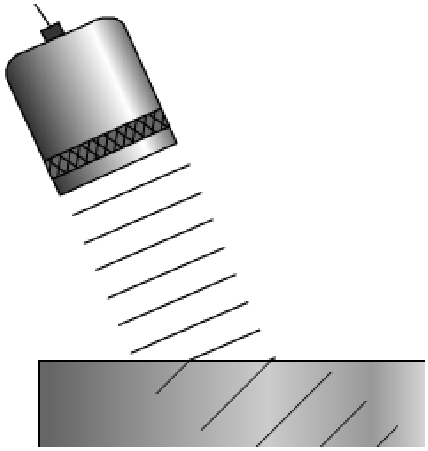
Q: *What portion of the signal will be reflected at an Air-Steel interface?*

A: *99.996%*

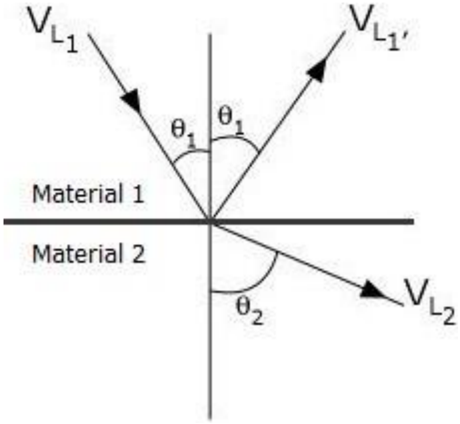
Refraction and Snell's Law

When an ultrasonic wave passes through an interface between two materials at an oblique angle, and the materials have different indices of refraction, both reflected and refracted waves are produced. This also occurs with light, which is why objects seen across an interface appear to be shifted relative to where they really are. For example, if you look straight down at an object at the bottom of a glass of water, it looks closer than it really is.

Refraction takes place at an interface of two materials due to the difference in acoustic velocities between the two materials. The figure shows the case where plane sound waves traveling in one material enters a second material that has a higher acoustic velocity. When the wave encounters the interface between these two materials, the portion of the wave in the second material is moving faster than the portion of the wave that is still in the first material. As a result, this causes the wave to bend and change its direction (*this is referred to as "refraction"*).



Snell's Law describes the relationship between the angles and the velocities of the waves. Snell's law equates the ratio of material velocities to the ratio of the sine's of incident and refracted angles, as shown in the following equation:



$$\boxed{\frac{\sin 1}{V_{L_1}} = \frac{\sin 2}{V_{L_2}}}$$

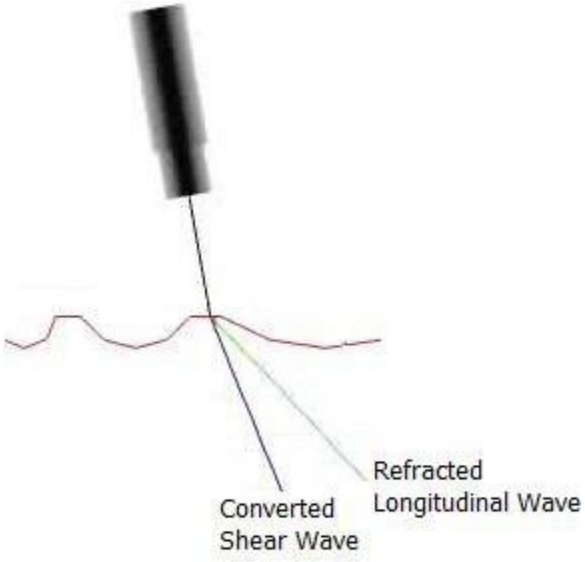
Where;

V_{L_1} & V_{L_2} : the longitudinal wave velocities in the first and second materials respectively
$_1$ & $_2$: the angles of incident and refracted waves respectively

Note that in the diagram, there is a reflected longitudinal wave (V_{L1_F}) shown. This wave is reflected at the same angle as the incident wave because the two waves are traveling in the same material, and hence have the same velocity. This reflected wave is unimportant in our explanation of Snell's Law, but it should be remembered that some of the wave energy is reflected at the interface.

Mode Conversion

When sound travels in a solid material, one form of wave energy can be transformed into another form. For example, when a longitudinal wave hits an interface at an angle, some of the energy can cause particle movement in the transverse direction to start a shear wave. *Mode conversion* occurs when a wave encounters an interface between materials of different acoustic impedances and the incident angle is not normal to the interface. It should be noted that mode conversion occurs "*every time*" a wave encounters an interface at an angle. This mode conversion occurs for both the portion of the wave that passes through the interface and the portion that reflects off the interface.



In the previous section, it was pointed out that when sound waves pass through an interface between materials having different acoustic velocities, refraction takes place at the interface. The larger the difference in acoustic velocities between the two materials, the more the sound is refracted. However, the converted shear wave is not refracted as much as the longitudinal wave because shear waves travel slower than longitudinal waves. Therefore, the velocity difference between the incident longitudinal wave and the shear wave is not as great as it is between the incident and refracted longitudinal waves. Also note that when a longitudinal wave is reflected inside the material, the reflected shear wave is reflected at a smaller angle than the reflected longitudinal wave. This is also due to the fact that the shear velocity is less than the longitudinal velocity within a given material.

Snell's Law holds true for shear waves as well as longitudinal waves and can be written as follows:

$$\boxed{\frac{\sin _1}{V_{L_1}} = \frac{\sin _2}{V_{L_2}} = \frac{\sin _3}{V_{S_1}} = \frac{\sin _4}{V_{S_2}}}$$

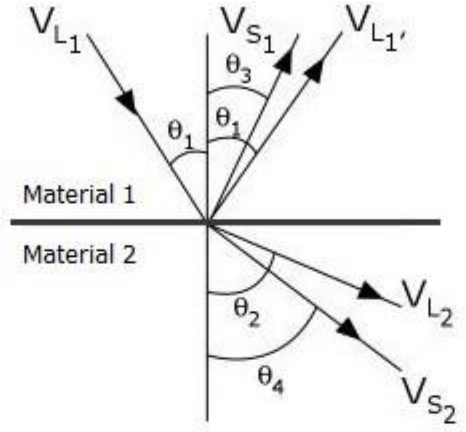
Where;

V_{L_1} & V_{L_2} : the longitudinal wave velocities in the first and second materials respectively

V_{S_1} & V_{S_2} : the shear wave velocities in the first and second materials respectively

$_1$ & $_2$: the angles of incident and refracted longitudinal waves respectively

$_3$ & $_4$: the angles of the converted reflected and refracted shear waves respectively



Critical Angles

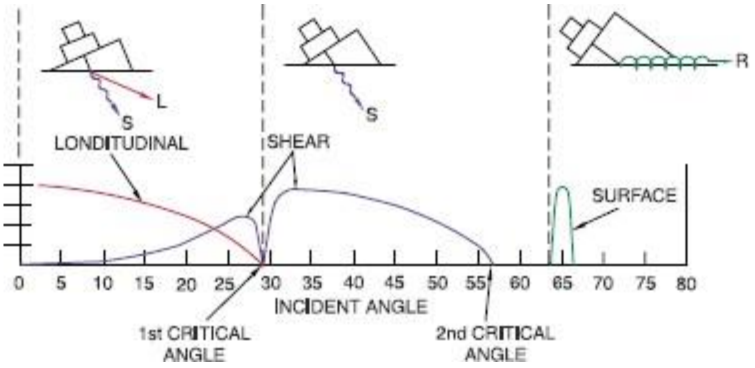
When a longitudinal wave moves from a slower to a faster material at an angle (*and thus the wave is refracted*), there is an incident angle that makes the angle of refraction of the "longitudinal wave" to become 90°. This is angle is known as "***the first critical angle***". The first critical angle can be found from Snell's law by putting in an angle of 90° for the angle of the refracted ray. At the critical angle of incidence, much of the acoustic energy is in the form of an inhomogeneous compression wave, which travels along the interface and decays exponentially with depth from the interface. This wave is sometimes referred to as a "*creep wave*". Because of their inhomogeneous nature and the fact that they decay rapidly, creep waves are not used as extensively as Rayleigh surface waves in NDT.

When the incident angle is greater than the first critical angle, only the mode converted shear wave propagates into the material. For this reason, most angle beam transducers use a shear wave so that the signal is not complicated by having two waves present.

In many cases there is also an incident angle that makes the angle of refraction for the "shear wave" to become 90°. This is known as the "***second critical angle***" and at this point, all of the wave energy is reflected or refracted into a surface following shear wave or shear creep wave. Slightly <u>beyond the second critical angle</u>, <u>surface (*Rayleigh*) waves will be generated</u>.

The <u>incident angle for angle-beam transducers</u> is somewhere <u>between the first and second critical angles</u> such that a shear wave, at a desired angle, is introduced into the material being inspected.

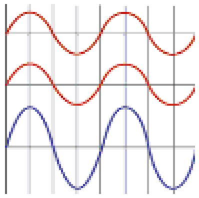
The figure shows the <u>mode of waves</u> introduced into a <u>steel</u> surface as a function of the incident angle of the wave generated by the transducer. It can be seen from the figure that the incident angle for angle beam (*shear*) transducers ranges between 30° to 55°. But it is important to remember that, due to refraction, the angle of the shear wave inside the material is completely different than the incident angle.



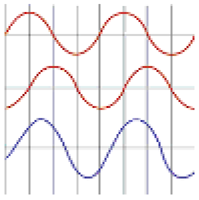
<u>Wave Interaction or Interference</u>

The understanding of the interaction or interference of waves is important for understanding the performance of an ultrasonic transducer. When sound emanates from an ultrasonic transducer, it does not originate from a single point, but instead originates from many points along the surface of the piezoelectric element. This results in a sound field with many waves interacting or interfering with each other.

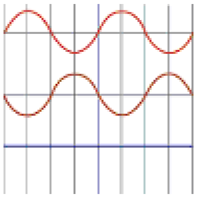
When waves interact, they superimpose on each other, and the amplitude of the sound pressure at any point of interaction is the sum of the amplitudes of the two individual waves. First, let's consider two identical waves that originate from the same point. When they are <u>*in phase*</u> (so that the peaks and valleys of one are exactly aligned with those of the other), they <u>combine to double the pressure</u> of either wave acting alone. When they are completely <u>*out of phase*</u> (so that the peaks of one wave are exactly aligned with the valleys of the other wave), they combine to <u>cancel each other</u> out. When the two waves are not completely in phase or out of phase, the resulting wave is the



In Phase
(0° phase difference)
Constructive Interference



90° phase difference



Out of Phase
(180° phase difference)
Destructive Interference

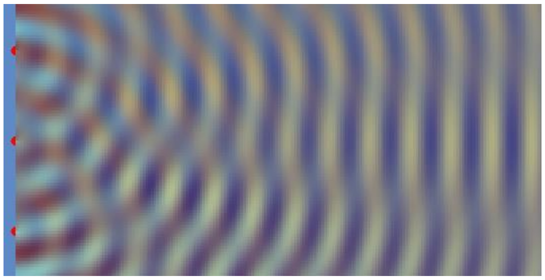
sum of the wave amplitudes for all points along the wave.

When the origins of the two interacting waves are not the same, it is a little harder to picture the wave interaction, but the principles are the same. Up until now, we have primarily looked at waves in the form of a 2D plot of wave amplitude versus wave position. However, anyone that has dropped something in a pool of water can picture the waves radiating out from the source with a circular wave front. If two objects are dropped a short distance apart into the pool of water, their waves will radiate out from their sources and interact with each other. At every point where the waves interact, the amplitude of the particle displacement is the combined sum of the amplitudes of the particle displacement of the individual waves.

Wave from one point

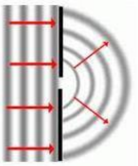
Interference of waves from two points

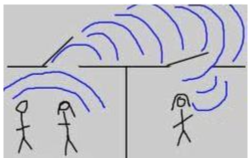
As stated previously, sound waves originate from multiple points along the face of the transducer. The image shows what the sound field would look like if the waves originated from just three points (*of course there are more than three points of origin along the face of a transducer*). It can be seen that the waves interact near the face of the transducer and as a result there are extensive fluctuations and the sound field is very uneven. In ultrasonic testing, this is known as the "*near field*" or Fresnel zone. The sound field is more uniform away from the transducer, in the "*far field*" or Fraunhofer zone. At some distance from the face of the transducer and central to the face of the transducer, a uniform and intense wave field develops.



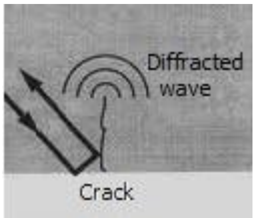
Wave Diffraction

Diffraction involves a change in direction of waves as they pass through an opening or around a barrier in their path. Diffraction of sound waves is commonly observed; we notice sound diffracting around corners or through door openings, allowing us to hear others who are speaking to us from adjacent rooms.





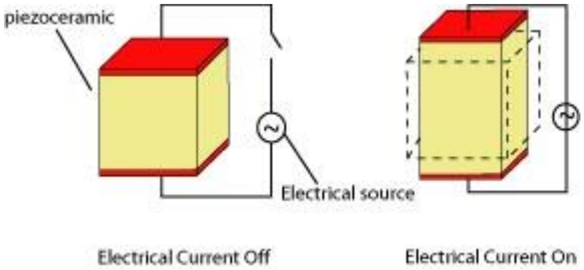
In ultrasonic testing of solids, diffraction patterns are usually generated at the edges of sharp reflectors (or discontinuities) such as cracks. Usually the tip of a crack behaves as point source spreading waves in all directions due to the diffraction of the incident wave.



EQUIPMENT & TRANSDUCERS

Piezoelectric Transducers

The conversion of electrical pulses to mechanical vibrations and the conversion of returned mechanical vibrations back into electrical energy is the basis for ultrasonic testing. This conversion is done by the transducer using a piece of piezoelectric material (*a polarized material having some parts of the molecule positively charged, while other parts of the molecule are negatively charged*) with electrodes attached to two of its opposite faces. When an electric field is applied across the material, the polarized molecules will align themselves with the electric field causing the material to change dimensions. In addition, a permanently-polarized material such as quartz (SiO_2) or barium titanate ($BaTiO_3$) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force. This phenomenon is known as the piezoelectric effect.

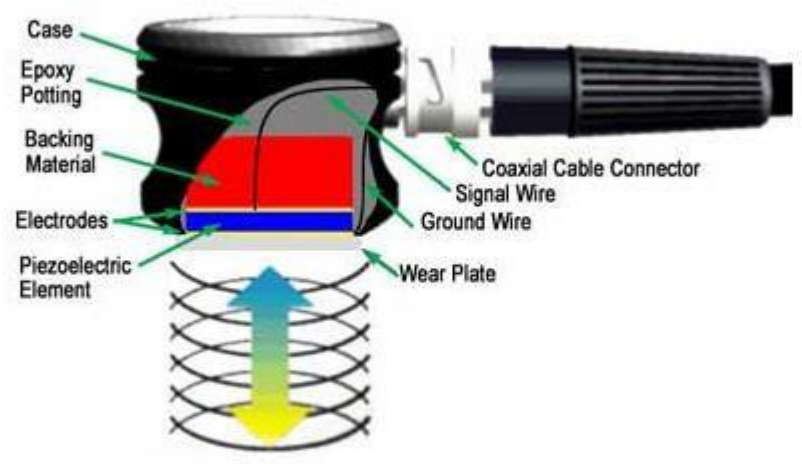


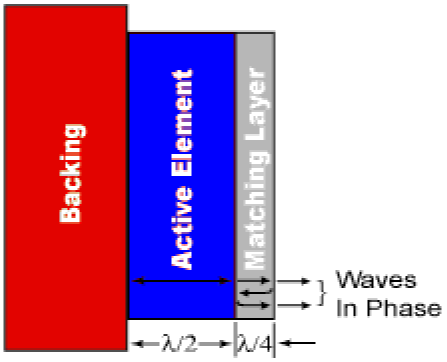
The active element of most acoustic transducers used today is a piezoelectric ceramic, which can be cut in various ways to produce different wave modes. A large piezoelectric ceramic element can be seen in the image of a sectioned low frequency transducer. The most commonly employed ceramic for making transducers is lead zirconate titanate.

The thickness of the active element is determined by the desired frequency of the transducer. A thin wafer element vibrates with a wavelength that is twice its thickness. Therefore, piezoelectric crystals are cut to a thickness that is 1/2 the desired radiated wavelength. The higher the frequency of the transducer, the thinner the active element is.

Characteristics of Piezoelectric Transducers

The function of the transducer is to convert electrical signals into mechanical vibrations (*transmit mode*) and mechanical vibrations into electrical signals (*receive mode*). Many factors, including material, mechanical and electrical construction, and the external mechanical and electrical load conditions, influence the behavior of a transducer.





A cut away of a typical contact transducer is shown in the figure. To get as much energy out of the transducer as possible, an impedance matching layer is placed between the active element and the face of the transducer. Optimal impedance matching is achieved by sizing the matching layer so that its thickness is 1/4 of the desired wavelength. This keeps waves that are reflected within the matching layer in phase when they exit the layer. For contact transducers, the matching layer is made from a material that has an acoustical impedance between the active element and steel. Immersion transducers have a matching layer with acoustical impedance between the active element and water. Contact transducers also incorporate a wear plate to protect the matching layer and active element from scratching.

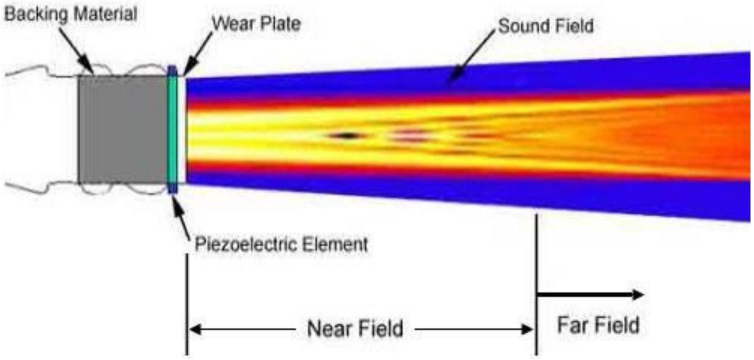
The backing material supporting the crystal has a great influence on the damping characteristics of a transducer. Using a backing material with an impedance similar to that of the active element will produce the most effective damping. Such a transducer will have a wider bandwidth resulting in higher sensitivity and higher resolution (*i.e., the ability to locate defects near the surface or in close proximity in the material*). As the mismatch in impedance between the active element and the backing material increases, material penetration increases but transducer sensitivity is reduced.

The bandwidth refers to the range of frequencies associated with a transducer. The frequency noted on a transducer is the central frequency and depends primarily on the backing material. Highly damped transducers will respond to frequencies above and below the central frequency. The broad frequency range provides a transducer with high resolving power. Less damped transducers will exhibit a narrower frequency range and poorer resolving power, but greater penetration.

The central frequency will also define the capabilities of a transducer. Lower frequencies (0.5MHz - 2.25MHz) provide greater energy and penetration in the material, while high frequency crystals (15.0MHz - 25.0MHz) provide reduced penetration but greater sensitivity to small discontinuities.

Radiated Fields of Ultrasonic Transducers

The sound that emanates from a piezoelectric transducer does not originate from a point, but instead originates from most of the surface of the piezoelectric element. The sound field from a typical piezoelectric transducer is shown in the figure where lighter colors indicating higher intensity. Since the ultrasound originates from a number of points along the transducer face, the ultrasound intensity along the beam is affected by constructive and destructive wave interference as discussed previously. This wave interference leads to extensive fluctuations in the sound intensity near the source and is known as the "*near field*". Because of acoustic variations within a near field, it can be extremely difficult to accurately evaluate flaws in materials when they are positioned within this area.



The pressure waves combine to form a relatively uniform front at the end of the near field. The area beyond the near field where the ultrasonic beam is more uniform is called the "*far field*". The transition between the near field and the far field occurs at a distance, N, and is sometimes referred to as the "*natural focus*" of a flat (*or unfocused*) transducer. Spherical or cylindrical focusing changes the structure of a transducer field by "pulling" the N point nearer the transducer. The area just beyond the near field is where the sound wave is well behaved and at its maximum strength. Therefore, optimal detection results will be obtained when flaws occur in this area.

For a round transducer (*often referred to as piston source transducer*), the near field distance can be found as:

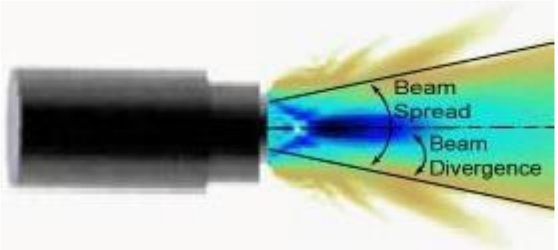
$$\boxed{N = \frac{D^2 f}{4V}}$$

Where;

D : transducer diameter, f : transducer frequency, and V: sound longitudinal velocity in the medium through which waves are transmitted.

Transducer Beam Spread

As the sound waves exits the near field and propegate through the material, the sound beam continiously spreads out. This phenomenon is usually referred to as beam spread but sometimes it is also referred to as beam divergence or ultrasonic diffraction. It should be noted that there is actually a difference between beam spread and beam divergence. Beam spread is a measure of the whole angle from side to side of the beam in the far field. Beam divergence is a measure of the angle from one side of the sound beam to the central axis of the beam in the far field. Therefore, beam spread is twice the beam divergence.



Although beam spread must be considered when performing an ultrasonic inspection, it is important to note that in the far field, or Fraunhofer zone, the maximum sound pressure is always found along the acoustic axis (*centerline*) of the transducer. Therefore, the strongest reflections are likely to come from the area directly in front of the transducer.

Beam spread occurs because the vibrating particle of the material (*through which the wave is traveling*) do not always transfer all of their energy in the direction of wave propagation. If the particles are not directly aligned in the direction of wave propagation, some of the energy will get transferred off at an angle. In the near field, constructive and destructive wave interference fill the sound field with fluctuation. At the start of the far field, however, the beam strength is always greatest at the center of the beam and diminishes as it spreads outward.

The beam spread is largely influenced by the frequency and diameter of the transducer. For a flat piston source transducer, an approximation of the beam divergence angle at which the sound pressure has decreased by one half (*-6 dB*) as compared to its value at the centerline axis can be caculated as:

$$\boxed{\sin\ = 1.2\ \frac{V}{D\,f}}$$

Where;

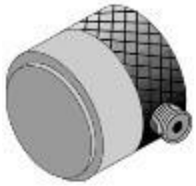
: the beam <u>divergence</u> angle from centerline to point where signal is at half strength
V : sound velocity in the material
D : diameter of the transducer
f : frequency of the transducer

Transducer Types

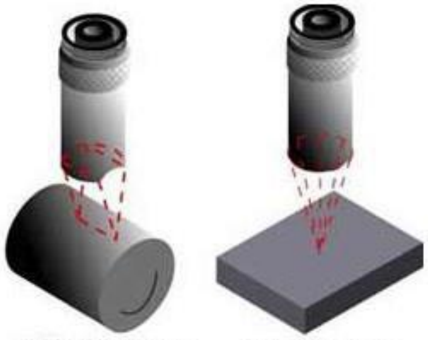
Ultrasonic transducers are manufactured for a variety of applications and can be custom fabricated when necessary. Careful attention must be paid to selecting the proper transducer for the application. It is important to choose transducers that have the desired frequency, bandwidth, and focusing to optimize inspection capability. Most often the transducer is chosen either to enhance the <u>sensitivity or resolution</u> of the system.

Transducers are classified into <u>two major groups</u> according to the application.

Contact transducers are used for direct contact inspections, and are generally hand manipulated. They have elements protected in a <u>rugged casing</u> to withstand sliding contact with a variety of materials. These transducers have an <u>ergonomic design</u> so that they are easy to grip and move along a surface. They often have <u>replaceable wear plates</u> to lengthen their useful life. Coupling materials of water, grease, oils, or commercial materials are used to remove the air gap between the transducer and the component being inspected.



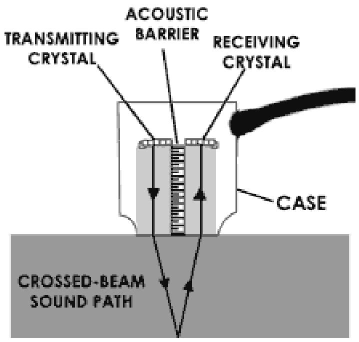
Immersion transducers do not contact the component. These transducers are designed to operate in a liquid environment and all connections are watertight. Immersion transducers usually have an impedance matching layer that helps to get more sound energy into the water and, in turn, into the component being inspected. Immersion transducers can be purchased with a <u>planer, cylindrically focused or spherically focused</u> lens. A focused transducer can improve the sensitivity and axial resolution by concentrating the sound energy to a smaller area. Immersion transducers are typically used inside a water tank or as part of a squirter or bubbler system in scanning applications.



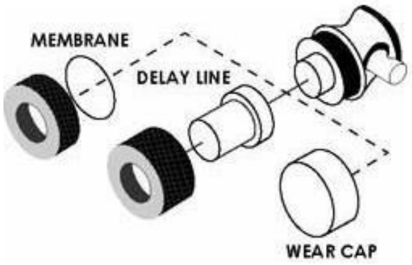
Cylindrical Focus Spherical Focus

Other Types of Contact Transducers

Contact transducers are available in a variety of configurations to improve their usefulness for a variety of applications. The flat contact transducer shown above is used in normal beam inspections of relatively flat surfaces, and where near surface resolution is not critical. If the surface is curved, a shoe that matches the curvature of the part may need to be added to the face of the transducer. If near surface resolution is important or if an angle beam inspection is needed, one of the special contact transducers described below might be used.

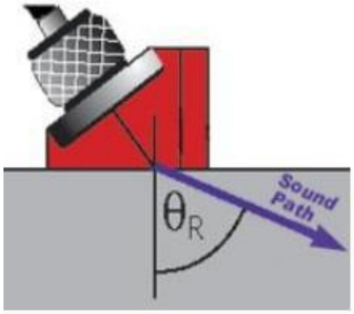


- *Dual element transducers* contain two independently operated elements in a single housing. One of the elements transmits and the other receives the ultrasonic signal. Dual element transducers are especially well suited for making measurements in applications where reflectors are very near the transducer since this design eliminates the ring down effect that single-element transducers experience (*when single-element transducers are operating in pulse echo mode, the element cannot start receiving reflected signals until the element has stopped ringing from its transmit function*). Dual element transducers are very useful when making thickness measurements of thin materials and when inspecting for near surface defects. The two elements are angled towards each other to create a crossed-beam sound path in the test material.



- *Delay line transducers* provide versatility with a variety of replaceable options. Removable delay line, surface conforming membrane, and protective wear cap options can make a single transducer effective for a wide range of applications. As the name implies, the primary function of a delay line transducer is to introduce a time delay between the generation of the sound wave and the arrival of any reflected waves. This allows the transducer to complete its "sending" function before it starts its "receiving" function so that near surface resolution is improved. They are designed for use in applications such as high precision thickness gauging of thin materials and delamination checks in composite materials. They are also useful in high-temperature measurement applications since the delay line provides some insulation to the piezoelectric element from the heat.

- *Angle beam transducers* and wedges are typically used to introduce a refracted shear wave into the test material. Transducers can be purchased in a variety of fixed angles or in adjustable versions where the user determines the angles of incidence and refraction. In the fixed angle versions, the angle of refraction that is marked on the transducer is only accurate for a particular material, which is usually steel. The most commonly used refraction angles for fixed angle transducers are 45°, 60° and 70°. The angled sound path allows the sound beam to be reflected from the backwall to improve detectability of flaws in and around welded areas. They are also used to generate surface waves for use in detecting defects on the surface of a component.

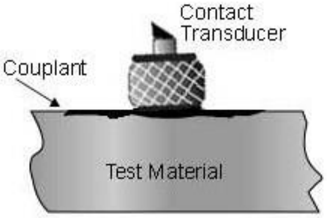


- *Normal incidence shear wave transducers* are unique because they allow the introduction of shear waves directly into a test piece without the use of an angle beam wedge. Careful design has enabled manufacturing of transducers with minimal longitudinal wave contamination.

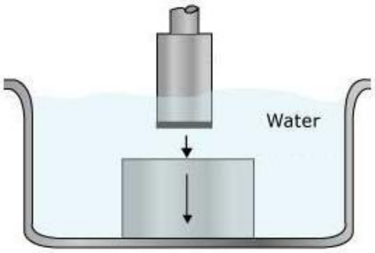
- *Paint brush transducers* are used to scan wide areas. These long and narrow transducers are made up of an array of small crystals and that make it possible to scan a larger area more rapidly for discontinuities. Smaller and more sensitive transducers are often then required to further define the details of a discontinuity.

Couplant

A couplant is a material (*usually liquid*) that facilitates the transmission of ultrasonic energy from the transducer into the test specimen. Couplant is generally necessary because the acoustic impedance mismatch between air and solids is large. Therefore, nearly all of the energy is reflected and very little is transmitted into the test material. The couplant displaces the air and makes it possible to get more sound energy into the test specimen so that a usable ultrasonic signal can be obtained. In contact ultrasonic testing a thin film of oil, glycerin or water is typically used between the transducer and the test surface. When shear waves are to be transmitted, the fluid is generally selected to have a significant viscosity.

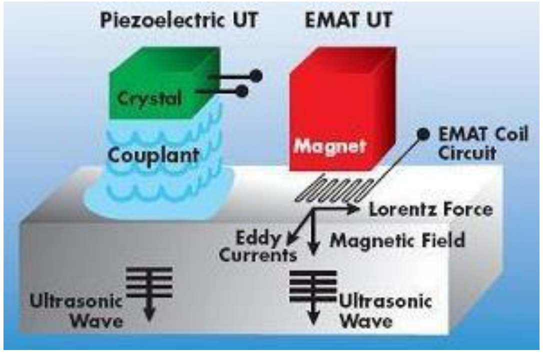


When scanning over the part, an immersion technique is often used. In immersion ultrasonic testing both the transducer and the part are immersed in the couplant, which is typically water. This method of coupling makes it easier to maintain consistent coupling while moving and manipulating the transducer and/or the part.

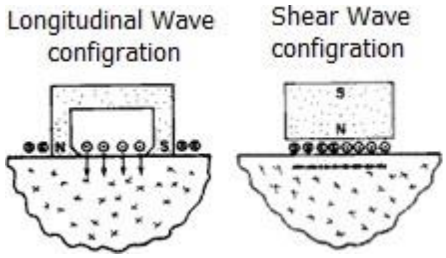


Electromagnetic Acoustic Transducers (*EMATs*)

Electromagnetic-acoustic transducers (*EMAT*) are a modern type of ultrasonic transducers that work based on a totally different physical principle than piezoelectric transducers and, most importantly, they do not need couplant. When a wire is placed near the surface of an electrically conducting object and is driven by a current at the desired ultrasonic frequency, eddy currents will be induced in a near surface region of the object. If a static magnetic field is also present, these eddy currents will experience forces called "*Lorentz forces*" which will cause pressure waves to be generated at the surface and propagate through the material.



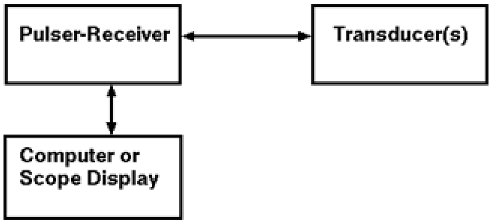
Different types of sound waves (*longitudinal, shear, lamb*) can be generated using EMATs by varying the configuration of the transducer such that the orientation of the static magnetic field is changed.



EMATs can be used for thickness measurement, flaw detection, and material property characterization. The EMATs offer many advantages based on its non-contact couplant-free operation. These advantages include the ability to operate in remote environments at elevated speeds and temperatures.

Pulser-Receivers

Ultrasonic pulser-receivers are well suited to general purpose ultrasonic testing. Along with appropriate transducers and an oscilloscope, they can be used for flaw detection and thickness gauging in a wide variety of metals, plastics, ceramics, and composites. Ultrasonic pulser-receivers provide a unique, low-cost ultrasonic measurement capability. Specialized portable equipment that are dedicated for ultrasonic inspection merge the pulser-receiver with the scope display in one small size battery operated unit.



The pulser section of the instrument generates short, large amplitude electric pulses of controlled energy, which are converted into short ultrasonic pulses when applied to an ultrasonic transducer. Control functions associated with the pulser circuit include:

- *Pulse length or damping*: The amount of time the pulse is applied to the transducer.
- *Pulse energy*: The voltage applied to the transducer. Typical pulser circuits will apply from 100 volts to 800 volts to a transducer.

In the receiver section the voltage signals produced by the transducer, which represent the received ultrasonic pulses, are amplified. The amplified signal is available as an output for display or capture for signal processing. Control functions associated with the receiver circuit include:

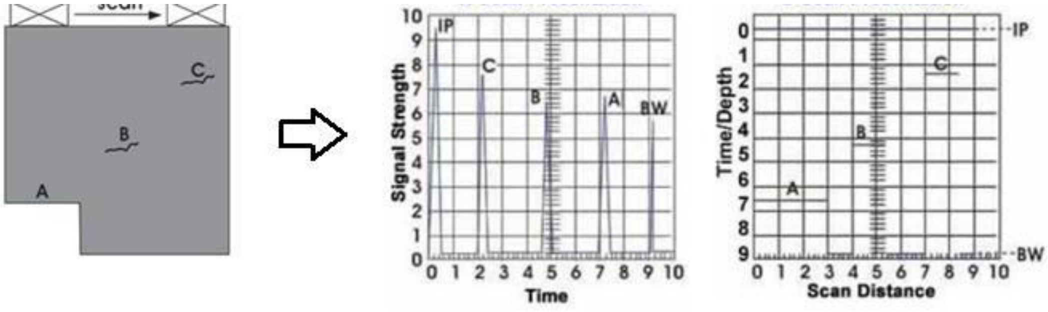
- *Signal rectification*: The signal can be viewed as positive half wave, negative half wave or full wave.
- *Filtering to shape and smoothing*
- *Gain, or signal amplification*
- *Reject control*

Data Presentation

Ultrasonic data can be collected and displayed in a number of different formats. The three most common formats are known in the NDT world as A-scan, B-scan and C-scan presentations. Each presentation mode provides a different way of looking at and evaluating the region of material being inspected. Modern computerized ultrasonic scanning systems can display data in all three presentation forms simultaneously.

A-Scan Presentation

The A-scan presentation displays the amount of received ultrasonic energy as a function of time. The relative amount of received energy is plotted along the vertical axis and the elapsed time (*which may be related to the traveled distance within the material*) is displayed along the horizontal axis. Most instruments with an A-scan display allow the signal to be displayed as a rectified signal, or as either the positive or negative half of the signal. In the A-scan presentation, relative discontinuity size can be estimated by comparing the signal amplitude obtained from an unknown reflector to that from a known reflector. Reflector depth can be determined by the position of the signal on the horizontal time axis.

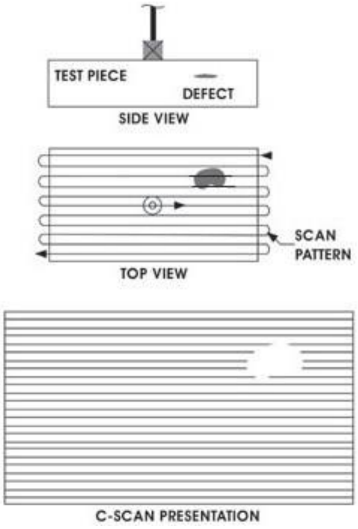


In the illustration of the A-scan presentation shown in the figure, the initial pulse generated by the transducer is represented by the signal ***IP***, which is near time zero. As the transducer is scanned along the surface of the part, four other signals are likely to appear at different times on the screen. When the transducer is in its far left position, only the ***IP*** signal and signal ***A***, the sound energy reflecting from surface ***A***, will be seen on the trace. As the transducer is scanned to the right, a signal from the backwall ***BW*** will appear later in time, showing that the sound has traveled farther to reach this surface. When the transducer is over flaw ***B***, signal ***B*** will appear at a point on the time scale that is approximately halfway between the ***IP*** signal and the ***BW*** signal. Since the ***IP*** signal corresponds to the front surface of the material, this indicates that flaw ***B*** is about halfway between the front and back surfaces of the sample. When the transducer is moved over flaw ***C***, signal ***C*** will appear earlier in time since the sound travel path is shorter and signal ***B*** will disappear since sound will no longer be reflecting from it.

B-Scan Presentation

The B-scan presentation is a type of presentation that is possible for automated linear scanning systems where it shows a profile (*cross-sectional*) view of the test specimen. In the B-scan, the time-of-flight (*travel time*) of the sound waves is displayed along the vertical axis and the linear position of the transducer is displayed along the horizontal axis. From the B-scan, the depth of the reflector and its approximate linear dimensions in the scan direction can be determined. The B-scan is typically produced by establishing a trigger gate on the A-scan. Whenever the signal intensity is great enough to trigger the gate, a point is produced on the B-scan. The gate is triggered by the sound reflected from the backwall of the specimen and by smaller reflectors within the material. In the B-scan image shown previously, line ***A*** is produced as the transducer is scanned over the reduced thickness portion of the specimen. When the transducer moves to the right of this section, the backwall line ***BW*** is produced. When the transducer is over flaws ***B*** and ***C***, lines that are similar in length to the flaws and at similar depths within the material are drawn on the B-scan. It should be noted that a limitation to this display technique is that reflectors may be masked by larger reflectors near the surface.

C-Scan Presentation



The C-scan presentation is a type of presentation that is possible for automated two-dimensional scanning systems that provides a plan-type view of the location and size of test specimen features. The plane of the image is parallel to the scan pattern of the transducer. C-scan presentations are typically produced with an automated data acquisition system, such as a computer controlled immersion scanning system. Typically, a data collection gate is established on the A-scan and the amplitude or the time-of-flight of the signal is recorded at regular intervals as the transducer is scanned over the test piece. The relative signal amplitude or the time-of-flight is displayed as a shade of gray or a color for each of the positions where data was recorded. The C-scan presentation provides an image of the features that reflect and scatter the sound within and on the surfaces of the test piece.

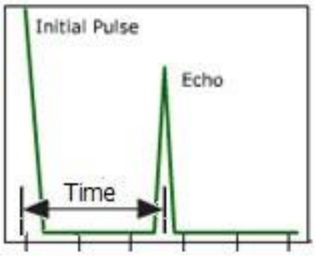
High resolution scans can produce very detailed images. The figure shows two ultrasonic C-scan images of a US quarter. Both images were produced using a pulse-echo technique with the transducer scanned over the head side in an immersion scanning system. For the C-scan image on the top, the gate was set to capture the amplitude of the sound reflecting from the front surface of the quarter. Light areas in the image indicate areas that reflected a greater amount of energy back to the transducer. In the C-scan image on the bottom, the gate was moved to record the intensity of the sound reflecting from the back surface of the coin. The details on the back surface are clearly visible but front surface features are also still visible since the sound energy is affected by these features as it travels through the front surface of the coin.

MEASUREMENT AND CALIBRATION TECHNIQUES

Normal Beam Inspection

Pulse-echo ultrasonic measurements can determine the location of a discontinuity in a part or structure by accurately measuring the time required for a short ultrasonic pulse generated by a transducer to travel through a thickness of material, reflect from the back or the surface of a discontinuity, and be returned to the transducer. In most applications, this time interval is a few microseconds or less. The two-way transit time measured is divided by two to account for the down-and-back travel path and multiplied by the velocity of sound in the test material. The result is expressed in the well-known relationship:

$$\boxed{d = \frac{V\,t}{2}}$$



Where d is the distance from the surface to the discontinuity in the test piece, V is the velocity of sound waves in the material, and t is the measured round-trip transit time.

Precision ultrasonic thickness gages usually operate at frequencies between 500 kHz and 100 MHz, by means of piezoelectric transducers that generate bursts of sound waves when excited by electrical pulses. Typically, lower frequencies are used to optimize penetration when measuring thick, highly attenuating or highly scattering materials, while higher frequencies will be recommended to optimize resolution in thinner, non-attenuating, non-scattering materials. It is possible to measure most engineering materials ultrasonically, including metals, plastic, ceramics, composites, epoxies, and glass as well as liquid levels and the thickness of certain biological specimens. On-line or in-process measurement of extruded plastics or rolled metal often is possible, as is measurements of single layers or coatings in multilayer materials.

Angle Beam Inspection

Angle beam transducers and wedges are typically used to introduce a refracted shear wave into the test material. An angled sound path allows the sound beam to come in from the side, thereby improving detectability of flaws in and around welded areas.

Angle beam inspection is somehow different than normal beam inspection. In normal beam inspection, the backwall echo is always present on the scope display and when the transducer basses over a discontinuity a new echo will appear between the initial pulse and the backwall echo. However, when scanning a surface using an angle beam transducer there will be no reflected echo on the scope display unless a properly oriented discontinuity or reflector comes into the beam path.

If a reflection occurs before the sound waves reach the backwall, the reflection is usually referred to as "*first leg reflection*". The angular distance (*Sound Path*) to the reflector can be calculated using the same formula used for normal beam transducers (*but of course using the shear velocity instead of the longitudinal velocity*) as:

$$\boxed{Sound\ Path = \frac{V_T\, t}{2}}$$

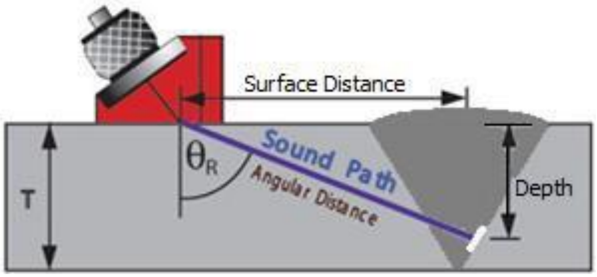
where V_T is the shear sound velocity in the material.

Knowing the angle of refraction for the transducer, the surface distance to the reflector and its depth can be calculated as:

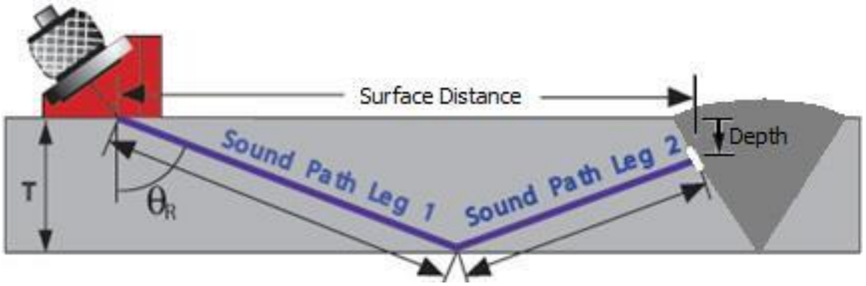
$$\boxed{Surface\ Distance = Sound\ Path\ \times \sin_R}$$

$$\boxed{Depth_{1^{st}\ l} = Sound\ Path\ \times \cos_R}$$

where $_R$ is the angle of refraction.



If a reflector came across the sound beam after it has reached and reflected off the backwall, the reflection is usually referred to as "*second leg reflection*". In this case, the "*Sound Path*" (the total sound path for the two legs) and the "*Surface Distance*" can be calculated using the same equations given above; however, the "*Depth*" of the reflector will be calculated as:



$$\boxed{Depth_{2^{nd}\ l} = 2\,T - (Sound\ Path\ \times \cos_R)}$$

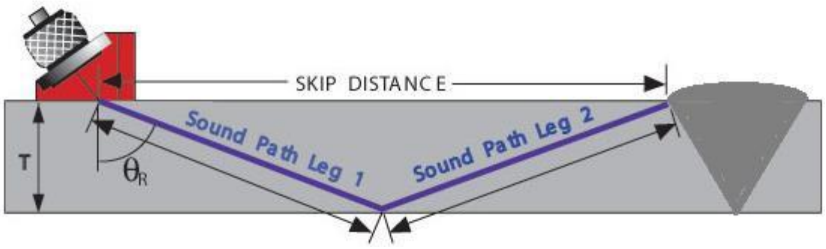
Inspection of Welded Joints

The most commonly occurring defects in welded joints are porosity, slag inclusions, lack of side-wall fusion, lack of intermediate-pass fusion, lack of root penetration, undercutting, and longitudinal or transverse cracks. With the exception of single gas pores all the listed defects are usually well detectable using ultrasonics.

Ultrasonic weld inspections are typically performed using straight beam transducer in conjunction with angle beam transducers.

- A normal beam transducer, producing a longitudinal wave at normal incidence into the test piece, is first used to locate any laminations in or near the heat-affected zone. This is important because an angle beam transducer may not be able to provide a return signal from a laminar flaw.
- The second step in the inspection involves using an angle beam transducer to inspect the actual weld. This inspection may include the root, sidewall, crown, and heat-affected zones of a weld. The process involves scanning the surface of the material around the weldment with the transducer. This refracted sound wave will bounce off a reflector (*discontinuity*) in the path of the sound beam.

To determine the proper scanning area for both sides of the weld, the inspector must calculate the skip distance of the sound beam using the refracted angle and material thickness as:



$\boxed{Skip\ Distance = 2\,T \times \tan{}_R}$ where T is the material thickness.

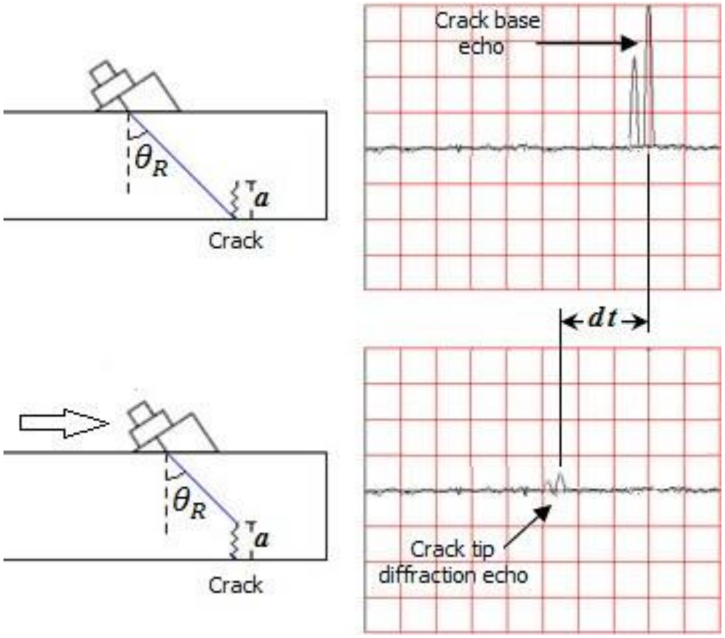
Based on such calculations, the inspector can identify the transducer locations on the surface of the material corresponding to the face, sidewall, and root of the weld.

The angle of refraction for the angle beam transducer used for inspection is usually chosen such that (${}_R = 90 - weldment\ bevel\ angle$). Doing so, the second leg of the beam will be normal to the side wall of the weldment such that lack of fusion can be easily detected (*the first leg will also be normal to the other wall*). However, for improving the detectability of the different types of weld discontinuities, it is recommended to repeat the scanning using several transducers having different angles of refraction.

Crack Tip Diffraction

When the geometry of the part is relatively uncomplicated and the orientation of a flaw is well known, the length of a crack can be determined by a technique known as “crack tip diffraction”.

One common application of the tip diffraction technique is to determine the length of a crack originating from on the backside of a flat plate as shown below. In this case, when an angle beam transducer is scanned over the area of the flaw, an echo appears on the scope display because of the reflection of the sound beam from the base of the crack (*top image*). As the transducer moves, a second, but much weaker, echo appears due to the diffraction of the sound waves at the tip of the crack (*bottom image*). However, since the distance traveled by the diffracted sound wave is less, the second signal appears earlier in time on the scope.

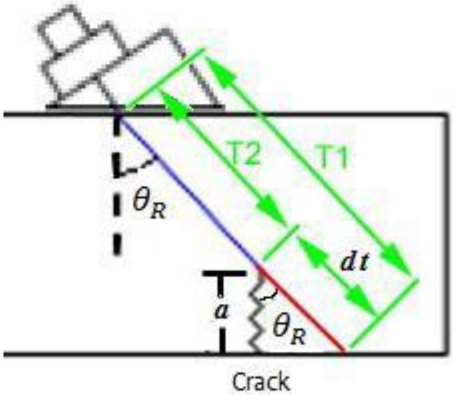


Crack height (a) is a function of the ultrasound shear velocity in the material (V_T), the incident angle ($_R$) and the difference in arrival times between the two signal (dt). Since the beam angle and the thickness of the material is the same in both measurements, two similar right triangles are formed such that one can be overlayed on the other. A third similar right triangle is made, which is comprised on the crack, the length dt and the angle $_R$. The variable dt is really the difference in time but can easily be converted to a distance by dividing the time in half (*to get the one-way travel time*) and multiplying this value by the velocity of the sound in the material. Using trigonometry, we can write:

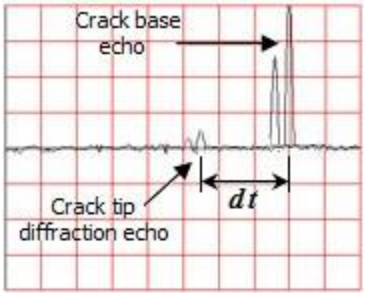
$$a = (Distance\ dt) \times \cos{}_R$$

Therefore, the crack height is found to be:

$$\boxed{a = (\frac{V_T\, dt}{2}) \times \cos \quad {}_R}$$



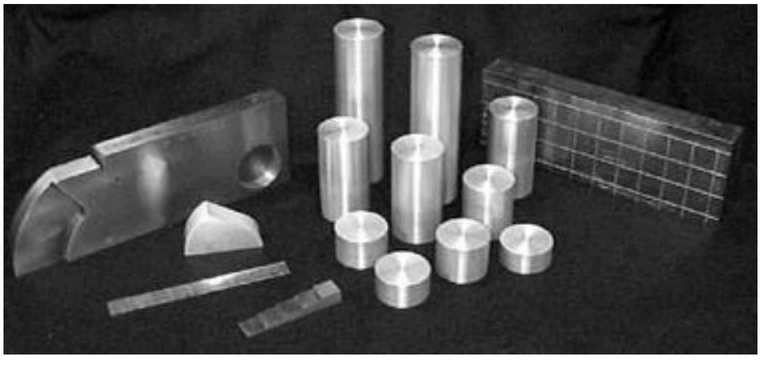
If the material is relatively thick or the crack is relatively short, the crack base echo and the crack tip diffraction echo could appear on the scope display simultaneously (*as seen in the figure*). This can be attributed to the divergence of the sound beam where it becomes wide enough to cover the entire crack length. In such case, though the angle of the beam striking the base of the crack is slightly different than the angle of the beam striking the tip of the crack, the previous equation still holds reasonably accurate and it can be used for estimating the crack length.



Calibration Methods

Calibration refers to the act of evaluating and adjusting the precision and accuracy of measurement equipment. In ultrasonic testing, several forms of calibrations must occur. First, the electronics of the equipment must be calibrated to ensure that they are performing as designed. This operation is usually performed by the equipment manufacturer and will not be discussed further in this material. It is also usually necessary for the operator to perform a "*user calibration*" of the equipment. This user calibration is necessary because most ultrasonic equipment can be reconfigured for use in a large variety of applications. The user must "calibrate" the system, which includes the equipment settings, the transducer, and the test setup, to validate that the desired level of precision and accuracy are achieved.

In ultrasonic testing, reference standards are used to establish a general level of consistency in measurements and to help interpret and quantify the information contained in the received signal. The figure shows some of the most commonly used reference standards for the calibration of ultrasonic equipment. Reference standards are used to validate that the equipment and the setup provide similar results from one day to the next and that similar results are produced by different systems. Reference standards also help the inspector to estimate the size of flaws. In a pulse-echo type setup, signal strength depends on both the size of the flaw and the distance between the flaw and the transducer. The inspector can use a reference standard with an artificially induced flaw of known size and at approximately the same distance away for the transducer to produce a



signal. By comparing the signal from the reference standard to that received from the actual flaw, the inspector can estimate the flaw size.

The material of the reference standard should be the same as the material being inspected and the artificially induced flaw should closely resemble that of the actual flaw. This second requirement is a major limitation of most standard reference samples. Most use drilled holes and notches that do not closely represent real flaws. In most cases the artificially induced defects in reference standards are better reflectors of sound energy (*due to their flatter and smoother surfaces*) and produce indications that are larger than those that a similar sized flaw would produce. Producing more "realistic" defects is cost prohibitive in most cases and, therefore, the inspector can only make an estimate of the flaw size.

Reference standards are mainly used to calibrate instruments prior to performing the inspection and, in general, they are also useful for:

- Checking the performance of both angle-beam and normal-beam transducers (*sensitivity, resolution, beam spread, etc.*)
- Determining the sound beam exit point of angle-beam transducers
- Determining the refracted angle produced
- Calibrating sound path distance
- Evaluating instrument performance (*time base, linearity, etc.*)

Introduction to Some of the Common Standards

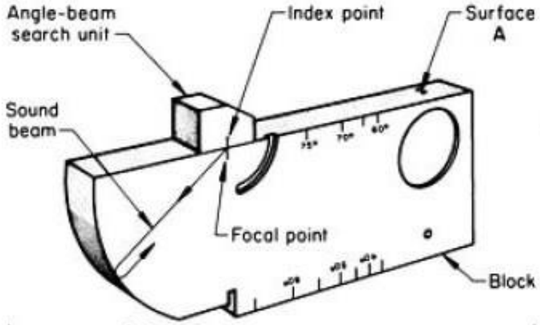
A wide variety of standard calibration blocks of different designs, sizes and systems of units (*mm or inch*) are available. The type of standard calibration block used is dependent on the NDT application and the form and shape of the object being evaluated. The most commonly used standard calibration blocks are those of the; International Institute of Welding (IIW), American Welding Society (AWS) and American Society of Testing and Materials (ASTM). Only two of the most commonly used standard calibration blocks are introduced here.

IIW Type US-1 Calibration Block

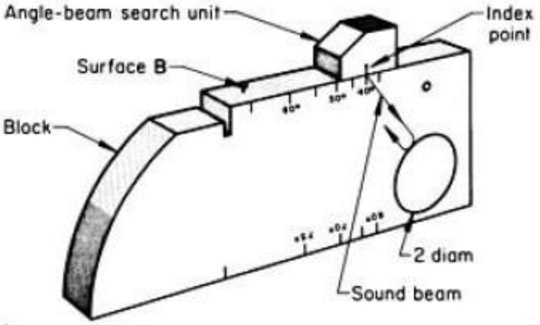
This block is a general purpose calibration block that can be used for calibrating angle-beam transducers as well as normal beam transducers. The material from which IIW blocks are prepared is specified as killed, open hearth or electric furnace, low-carbon steel in the normalized condition and with a grain size of McQuaid-Ehn No. 8 (*fine grain*). Official IIW blocks are dimensioned in the metric system of units.

The block has several features that facilitate checking and calibrating many of the parameters and functions of the transducer as well as the instrument where that includes; angle-beam exit (*index*) point, beam angle, beam spared, time base, linearity, resolution, dead zone, sensitivity and range setting.

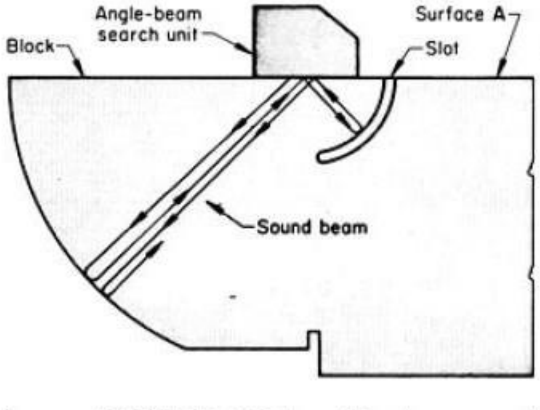
The figure below shows some of the uses of the block.



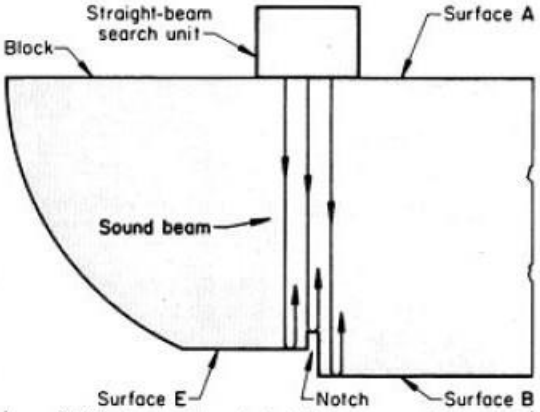
(a) Determination of index point



(b) Determination of beam angle



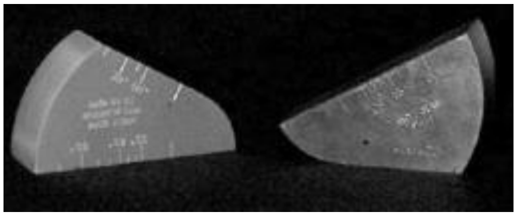
(c) Calibration of instrument time base



(d) Determination of straight-beam resolution

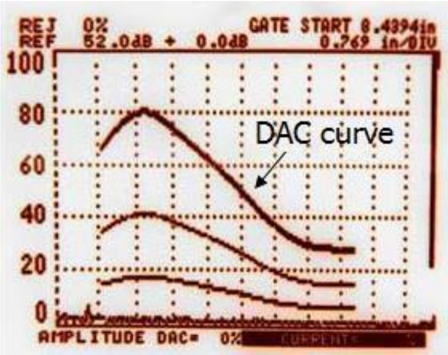
ASTM - Miniature Angle-Beam Calibration Block (V2)

The miniature angle-beam block is used in a somewhat similar manner as the as the IIW block, but is smaller and lighter. The miniature angle-beam block is primarily used in the field for checking the characteristics of angle-beam transducers.

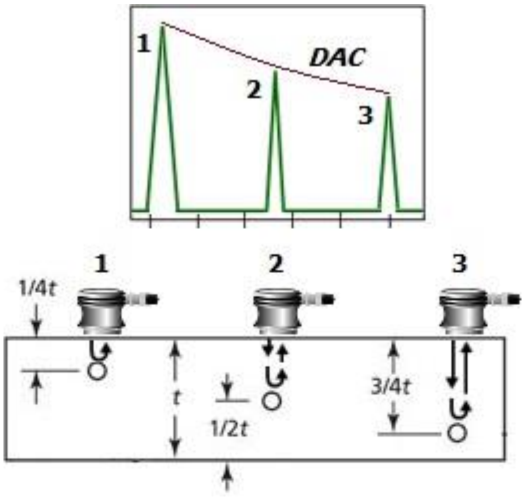


With the miniature block, beam angle and exit point can be checked for an angle-beam transducer. Both the 25 and 50 mm radius surfaces provide ways for checking the location of the exit point of the transducer and for calibrating the time base of the instrument in terms of metal distance. The small hole provides a reflector for checking beam angle and for setting the instrument gain.

Distance Amplitude Correction (DAC)



Acoustic signals from the same reflecting surface will have different amplitudes at different distances from the transducer. A distance amplitude correction (DAC) curve provides a means of establishing a graphic "reference level sensitivity" as a function of the distance to the reflector (*i.e., time on the A-scan display*). The use of DAC allows signals reflected from similar discontinuities to be evaluated where signal attenuation as a function of depth has been correlated. DAC will allow for loss in amplitude over material depth (time) to be represented graphically on the A-scan display. Because near field length and beam spread vary according to transducer size and frequency, and materials vary in attenuation and velocity, a DAC curve must be established for each different situation. DAC may be employed in both longitudinal and shear modes of operation as well as either contact or immersion inspection techniques.



A DAC curve is constructed from the peak amplitude responses from reflectors of equal area at different distances in the same material. Reference standards which incorporate side drilled holes (SDH), flat bottom holes (FBH), or notches whereby the reflectors are located at varying depths are commonly used. A-scan echoes are displayed at their non-electronically compensated height and the peak amplitude of each signal is marked to construct the DAC curve as shown in the figure. It is important to recognize that regardless of the type of reflector used, the size and shape of the reflector must be constant.

The same method is used for constructing DAC curves for angle beam transducers, however in that case both the first and second leg reflections can be used for constructing the DAC curve.