Non-Destructive Examination

Module 6

Module 6 – Inspection

- 6A – Non-Destructive Examination (NDE) Overview
- 6A.1 – Visual Inspection (VT)
- 6A.2 – Liquid Penetrant Testing (PT)
- 6A.3 – Magnetic Particle Testing (MT)
- 6A.4 – Eddy Current Testing (ECT)
- 6A.5 – Radiographic Testing (RT)
- 6A.6 – Ultrasonic Testing (UT)
- 6A.7 – NDE Advancements
- 6A.8 – NDE Qualification
- 6B – Fitness-for-Service
- 6J – ASME Section XI – Rules for Inservice Inspection of Nuclear Power Plant Components

Module 6 Learning Objectives

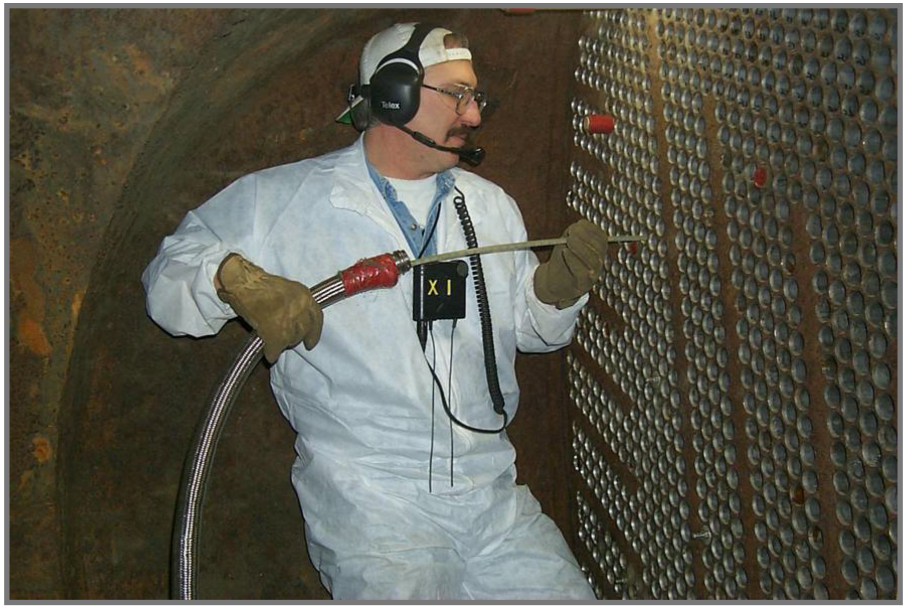
- Familiarize participants with NDE methods and their advantages and limitations
- Flaw Definitions and Classifications
- NDE Process Selection Guidelines
- NDE Personnel Qualification
- Pre-Service Inspection (PSI)
- In-Service Inspection (ISI)

Non-Destructive Evaluation Overview

Module 6A

Definition of NDE

- The use of noninvasive techniques to determine the integrity of a material, component, or structure
- Quantitatively measure some characteristic of an object
- Ideal conditions
  - NDE allows inspection or measurement without doing harm to the structure
  - NDE enables engineers to relate inspection data to service conditions in a manner that allows prediction and/or prevention of failures



Methods of NDE

- Methods covered in this course
  - Visual Testing (VT)
  - Liquid Penetrant Testing (PT)
  - Magnetic Particle Testing (MT)
  - Eddy Current Testing (ECT)
  - Radiographic Testing (RT)
  - Ultrasonic Testing (UT)
- Methods not covered
  - Acoustic Emission (AE)
  - Leak Testing
  - Optical Inspection
    - Optical Interferometry
    - Shearography
    - Holography
    - Digital Image Enhancement
  - Metrology
  - Thermography
  - Microwave

Review of Weld Defect Types

- Fabrication-related
  - Associated with primary fabrication or repair
  - Can be controlled by combination of metallurgical and welding process factors
  - Use of appropriate inspection techniques is critical
- Service-related
  - Occur upon exposure to service environment
  - Generally mechanically or environmentally induced
  - May result from remnant weld defects or metallurgical phenomena associated with the weld thermal cycle
  - Inspection and design issues are important to control defect formation and monitor propagation

Review of Weld Defect Types

- Fabrication-Related Defects
  - Lack-of-fusion (LOF)
  - Weld undercut
  - Excessive overbead or drop through
  - Lack of penetration (LOP) or incomplete penetration
  - Slag inclusions
  - Porosity, voids
  - Craters, melt-through, spatter, arc-strikes, underfill
  - Sugaring
    - Oxidation of root pass
  - Cracks
- Service-Related Damage Mechanisms
  - Hydrogen-induced
  - Corrosion and Corrosion-fatigue
  - Fatigue
  - Creep and creep-fatigue

Flaw Definitions and Classifications

Volumetric Flaws	Planar Flaws
Porosity	Seams
Inclusions (e.g., Slag, Tungsten, etc.)	Lamination
Shrinkage	Lack of bonding
Holes and voids	Forging/rolling lap
Corrosion thinning/loss	Casting shut
Corrosion pitting	Fatigue cracks
Porosity	Stress corrosion cracks
	Lack of fusion
	Incomplete penetration

NDE Process Selection and Guidelines

- Volumetric Flaws
  - Surface Breaking
    - Visual, Liquid Penetrant, or Optical Inspection
  - Near Surface
    - Magnetic Particle and Eddy Current
  - Microwave
  - Ultrasonic Testing (internal flaws)
  - Radiography
  - Thermography

- Planar Flaws
  - Surface Breaking
    - Visual
  - Near Surface
    - Magnetic Particle and Eddy Current
  - Microwave
  - Ultrasonic Testing (internal flaws)
  - Acoustic Emission
  - Thermography

ASME Section V – NDE Method vs.Type of Defect

TABLE A-110
IMPERFECTION VS TYPE OF NDE METHOD

	Surface [Note (1)]		Sub-surf. [Note (2)]		Volumetric [Note (3)]				
	VT	PT	MT	ET	RT	UTA	UTS	AE	UTT
Service-Induced Imperfections									
Abrasive Wear (Localized)	●	◑	◑	. . .	●	◑	◑	. . .	◑
Baffle Wear (Heat Exchangers)	●	. . .	. . .	◑	. . .	. . .	. . .	. . .	. . .
Corrosion-Assisted Fatigue Cracks	○	◑	●	. . .	○	●	. . .	●	. . .
Corrosion -Crevice	●	. . .	. . .	. . .	. . .	. . .	. . .	. . .	○
-General / Uniform	. . .	. . .	. . .	○	◑	. . .	◑	. . .	●
-Pitting	●	●	○	. . .	●	○	○	◑	○
-Selective	●	●	○	. . .	. . .	. . .	. . .	. . .	○
Creep (Primary) [Note (4)]	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Erosion	●	. . .	. . .	. . .	●	○	◑	. . .	◑
Fatigue Cracks	○	●	●	◑	◑	●	. . .	●	. . .
Fretting (Heat Exchanger Tubing)	◑	. . .	. . .	◑	. . .	. . .	. . .	. . .	◑
Hot Cracking	. . .	◑	◑	. . .	◑	○	. . .	◑	
Hydrogen-Induced Cracking	. . .	◑	◑	. . .	○	◑	. . .	◑	. . .
Intergranular Stress-Corrosion Cracks	. . .	. . .	. . .	. . .	. . .	○	. . .	. . .	. . .
Stress-Corrosion Cracks (Transgranular)	○	◑	●	○	◑	◑	. . .	◑	. . .

● – All or most standard techniques will detect this imperfection under all or most conditions.
◑ – One or more standard technique(s) will detect this imperfection under certain conditions.
○ – Special techniques, conditions, and/or personnel qualifications are required to detect this imperfection.

NOTES:
(1) Methods capable of detecting imperfections that are open to the surface only.
(2) Methods capable of detecting imperfections that are either open to the surface or slightly subsurface.
(3) Methods capable of detecting imperfections that may be located anywhere within the examined volume.

ASME Section V – NDE Method vs. Type of Defect

TABLE A-110
IMPERFECTION VS TYPE OF NDE METHOD

	Surface [Note (1)]		Sub-surf. [Note (2)]		Volumetric [Note (3)]				
	VT	PT	MT	ET	RT	UTA	UTS	AE	UTT
Welding Imperfections									
Burn Through	●	...	...	...	●	◑	...	...	○
Cracks	○	●	●	◑	◑	●	○	●	...
Excessive/Inadequate Reinforcement	●	...	...	...	●	◑	○	...	○
Inclusions (Slag/Tungsten)	...	...	◑	◑	●	◑	○	○	...
Incomplete Fusion	◑	...	◑	◑	◑	●	◑	◑	...
Incomplete Penetration	◑	●	●	◑	●	●	◑	◑	...
Misalignment	●	...	...	...	●	◑	...	...	...
Overlap	◑	●	●	○	...	○	...	...	...
Porosity	●	●	○	...	●	◑	○	○	...
Root Concavity	●	...	...	...	●	◑	○	○	○
Undercut	●	◑	◑	○	●	◑	○	○	...

● – All or most standard techniques will detect this imperfection under all or most conditions.
◑ – One or more standard technique(s) will detect this imperfection under certain conditions.
○ – Special techniques, conditions, and/or personnel qualifications are required to detect this imperfection.

NOTES:
(1) Methods capable of detecting imperfections that are open to the surface only.
(2) Methods capable of detecting imperfections that are either open to the surface or slightly subsurface.
(3) Methods capable of detecting imperfections that may be located anywhere within the examined volume.

ASME Section V Guidance on NDE Method vs. Type of Defect

TABLE A-110
IMPERFECTION VS TYPE OF NDE METHOD

	Surface [Note (1)]		Sub-surf. [Note (2)]		Volumetric [Note (3)]				
	VT	PT	MT	ET	RT	UTA	UTS	AE	UTT
Product Form Imperfections									
Bursts (Forgings)	○	●	●	◑	◑	◑	◑	●	...
Cold Shuts (Castings)	○	●	●	○	●	◑	◑	○	...
Cracks (All Product Forms)	○	●	●	◑	◑	◑	○	●	
Hot Tear (Castings)	○	●	●	◑	◑	◑	○	○	...
Inclusions (All Product Forms)	...	...	◑	◑	●	◑	○	○	...
Lamination (Plate, Pipe)	○	◑	◑	...	...	○	●	○	●
Laps (Forgings)	○	●	●	○	◑	...	○	○	
Porosity (Castings)	●	●	○	...	●	○	○	○	...
Seams (Bar, Pipe)	○	●	●	◑	○	◑	◑	○	...

● – All or most standard techniques will detect this imperfection under all or most conditions.
◑ – One or more standard technique(s) will detect this imperfection under certain conditions.
○ – Special techniques, conditions, and/or personnel qualifications are required to detect this imperfection.

NOTES:
(1) Methods capable of detecting imperfections that are open to the surface only.
(2) Methods capable of detecting imperfections that are either open to the surface or slightly subsurface.
(3) Methods capable of detecting imperfections that may be located anywhere within the examined volume.

NDE Personnel Certification

- American Society for Nondestructive Testing (ASNT)
  - www.asnt.org
- The British Institute of Non-Destructive Testing (PCN Cerification)
  - www.bindt.org
- CSWIP Certification Scheme for Welding & Inspection Personnel
  - www.cswip.com
- Natural Resources Canada
  - www.nrcan-rncan.gc.ca/mms-smm/ndt-end/index-eng.htm

NDE Personnel Qualification Levels

- Personnel certification levels
  - Level I
    - Follow procedures and techniques approved by Level III
    - Not allowed to interpret and evaluate for acceptance or rejection
    - Supervised and guided by Level II or Level III
  - Level II
    - Performs, evaluates, and documents results in accordance with written procedure approved by Level III
    - Guides and supervises Level I
  - Level III
    - Interprets codes, standards, and other contractual documents
    - Develops procedures
    - Conducts training and examination of NDT personnel
    - Chooses the inspection method
    - Level III approves procedures for technical adequacy

Performance Demonstration

- In some cases personnel must demonstrate performance on flawed samples prior to inspection
- Demonstrations are in addition to personnel certifications
- Performance demonstrations require specific levels of flaw detection and sizing on samples representative of components to be inspected

Inspection Types

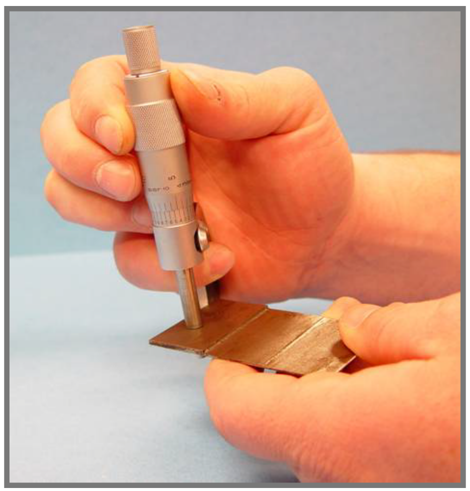
- Construction Inspection
  - Conducted during the fabrication of the component
    - As designated per ASME Section III or other construction code
- Pre-service Inspection
  - Conduct preoperational examinations prior to initial operation of equipment or a facility to establish a baseline condition
    - As designated per ASME Section III or other construction code
- Inservice Inspection
  - Subsequent examinations for comparison to original (PSI) condition to determine and indentify any changes or growth of a flaw
    - As designated per ASME Section XI or other in-service inspection code

Visual Inspection

Module 6A.1

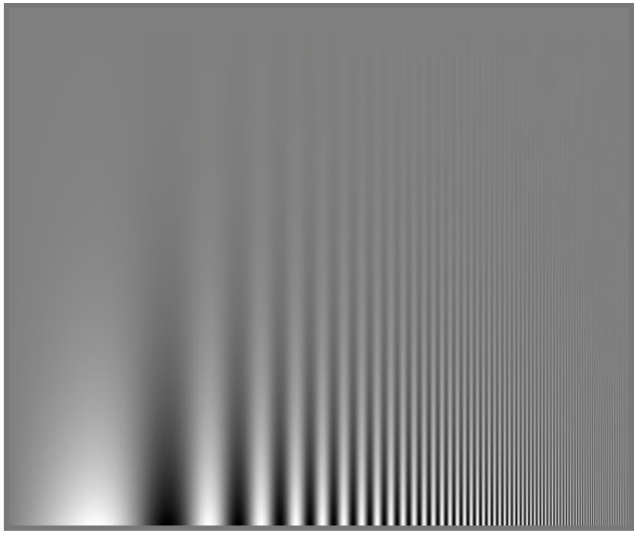
Introduction

- Four primary factors affect the quality of a visual inspection
  - Quality of the detector (eye or camera)
  - Lighting conditions
  - Capability to process the visual data
  - Level of training and attention to detail



Contrast Sensitivity

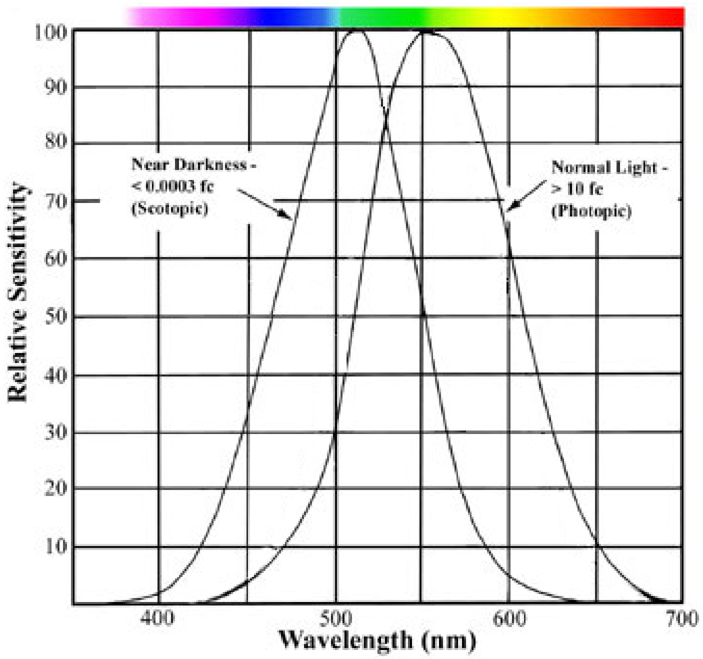
- Contrast sensitivity is a measure of how faded or washed out an object can be before it becomes indistinguishable from a uniform field
  - The human eye can detect is about 2% of full brightness
- Contrast sensitivity varies with
  - The size or spatial frequency of a feature
  - The lighting conditions
  - Whether the object is lighter or darker than the background



Campbell, F. W. and Robson, J. G. (1968) Application of Fourier analysis to the visibility of gratings. Journal of Physiology (London) Image Courtesy of Izumi Ohzawa, Ph.D. University of California School of Optometry

Light Levels

- Under normal lighting conditions the eye has good visual acuity and is most sensitive to greenish yellow color, which has a wavelength around 555 nanometers (photopic curve)
- At this very low light level, sensitivity to blue, violet, and ultraviolet is increased, but sensitivity to yellow and red is reduced

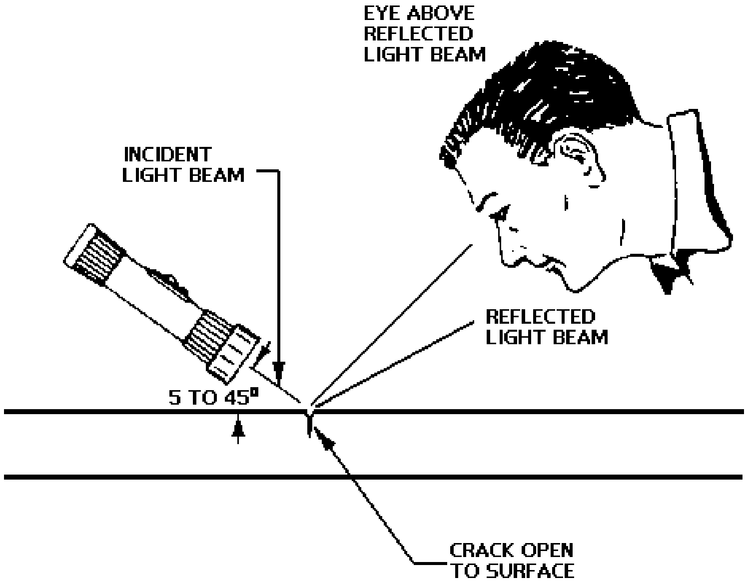


Light Intensity Measurement

- Effective visual inspection requires adequate lighting
- Specification requirements for lighting should be reviewed prior to performing an inspection
- Light Intensity monitors like that shown to the right ensure that the specification is being followed

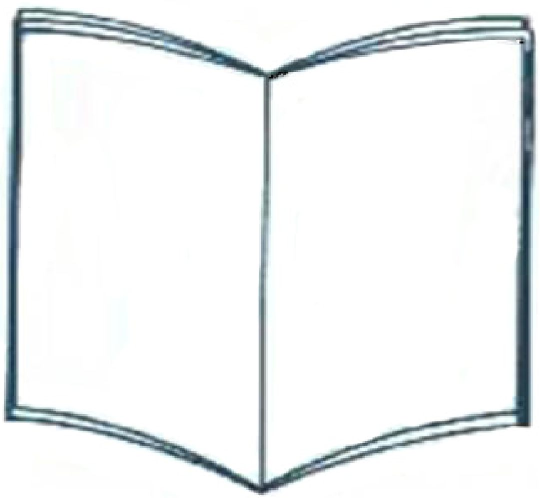
Light Directionality

- The directionality of the light is a very important consideration
- For some applications, flat, even lighting works well
- For other applications, directional lighting is better because it produces shadows that are larger than the actual flaw and easier to detect

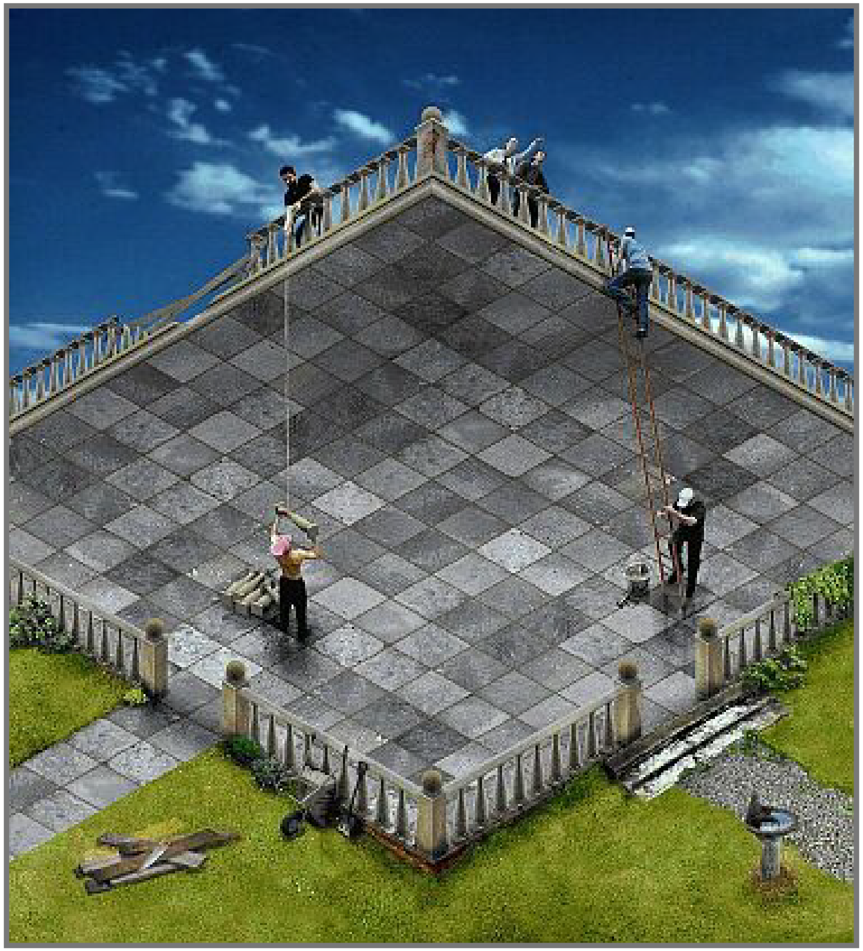


Perspective

The eye/brain need visual clues to determine perspective.

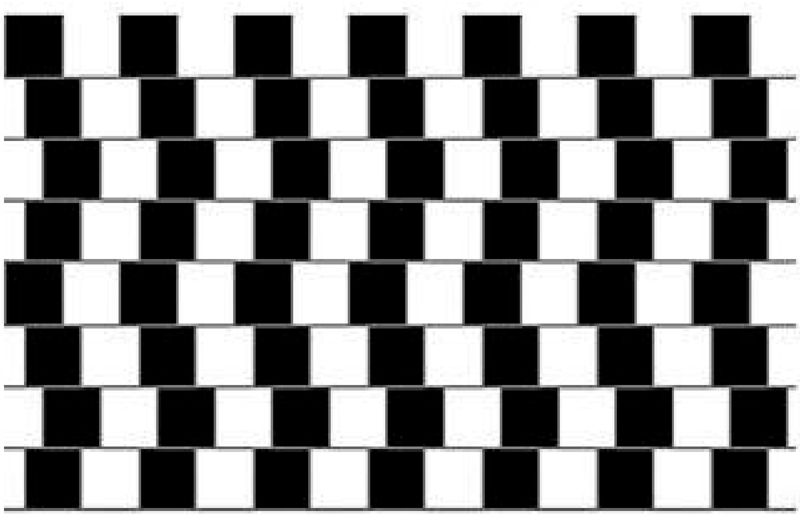


Is the book facing towards or away from you?

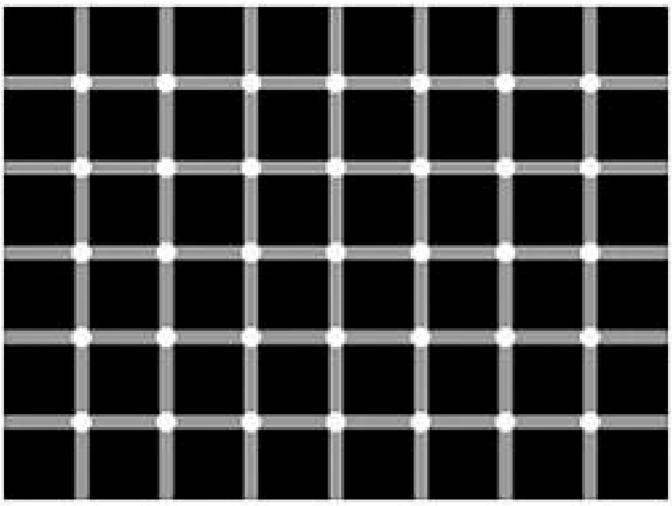


Optical Illusions

Sometime the eye/mind has trouble correctly processing visual information



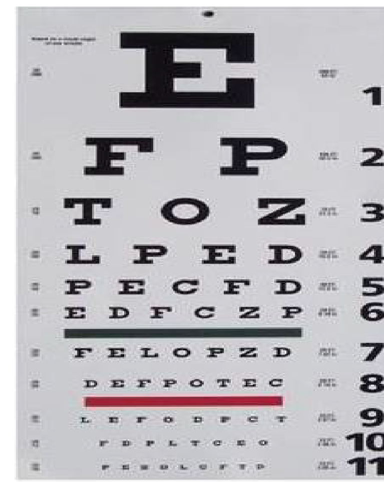
Are the horizontal lines parallel or do they slope?

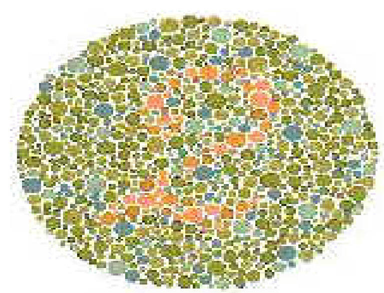


How many black dots do you see?

Basic Principles – Vision

- When evaluations are made by an inspector, eye examinations must be done at regular intervals to assure accuracy and sensitivity
  - Near Vision (Jaeger)
  - Far Vision (Snellen)
  - Color Differentiation
- When using machine vision, different but similar performance checks must be performed





Manual vs Automated Inspection

- Majority of visual inspections are completed by an inspector, but machine vision is becoming more common
  - Inspector has ability to quickly adapt to a variety of lighting and other non-typical conditions, and ability to use other senses
  - Machine vision inspection system has the ability to make very consistent and rapid inspections of specific details of a component

Alignment & Distortion

- Visual inspection frequently involves checking materials and components for fit and alignment
- Many standards establish allowable tolerances for fit and distortion

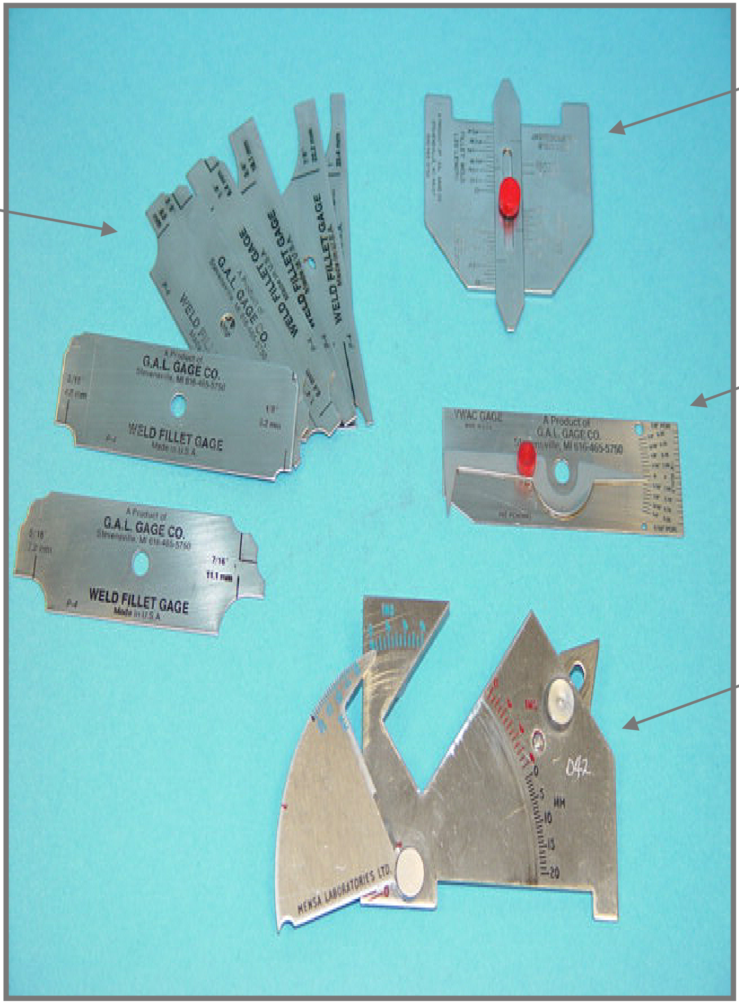
A fabricated girder is being inspected for distortion, sweep and web flatness

Equipment

- Visual inspection equipment includes a variety of different tools
  - Rulers, tape measures and spring type calipers
  - Rigid or flexible borescopes
  - Remote crawlers with cameras
- Many tools have been designed for specific applications such as the various weld gauges
- Some of the specialized tools such as crawlers have been designed to satisfy the inspection needs in applications where conventional techniques are not feasible

Dimensional Conformance of Welds

Fillet gauge set

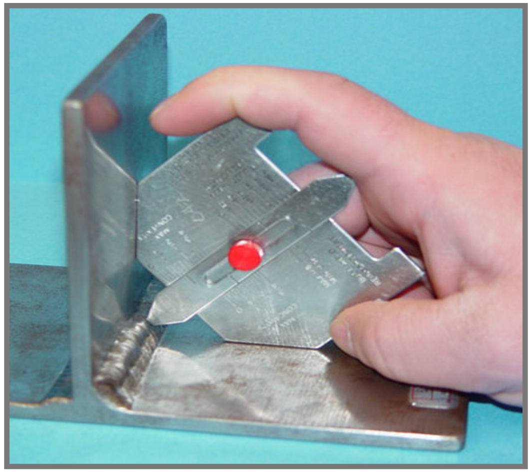


Palmgren gauge

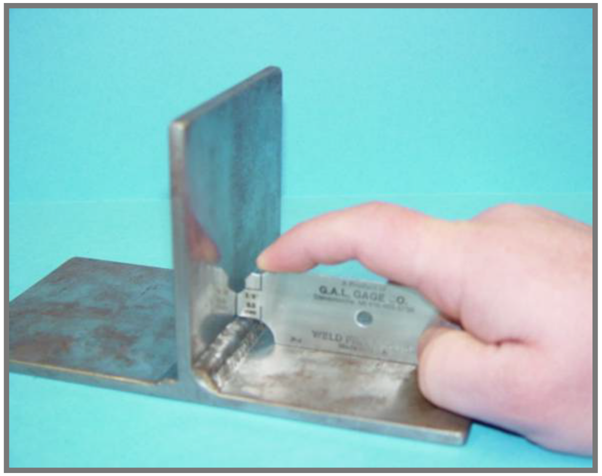
VWAC gauge

Cambridge gauge

Dimensional Conformance of Welds



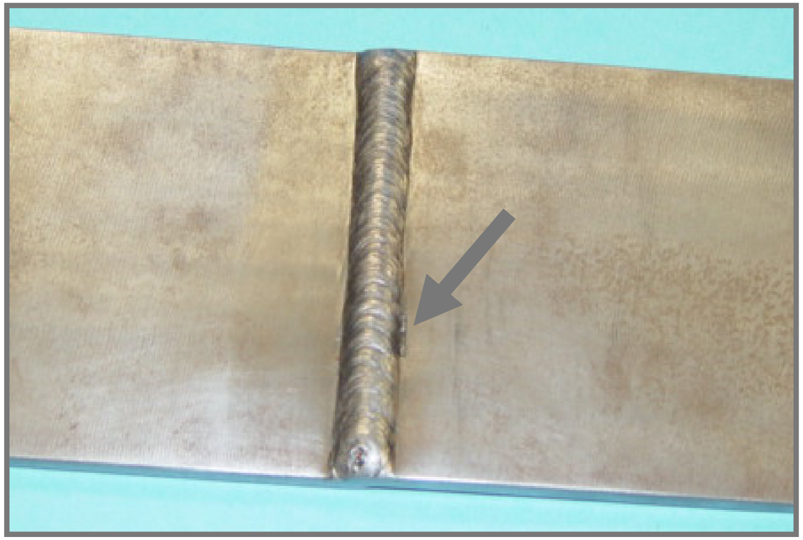
Throat measurement using a Palmgren gauge

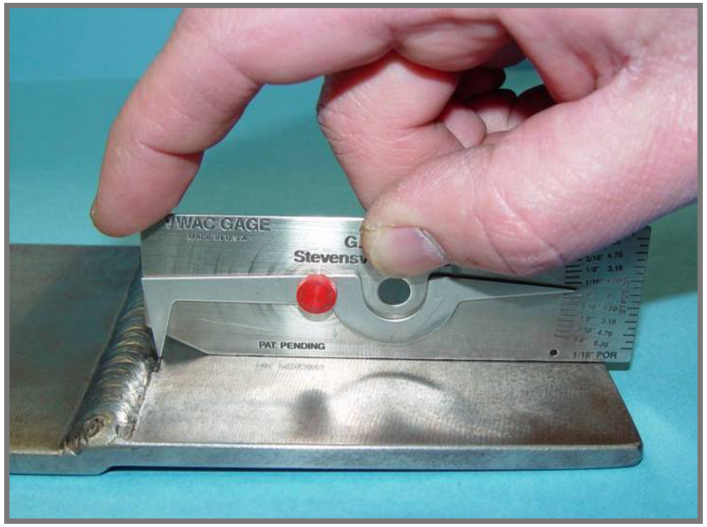


Leg size determination with fillet gauge

Convexity measurement with VWAC gauge

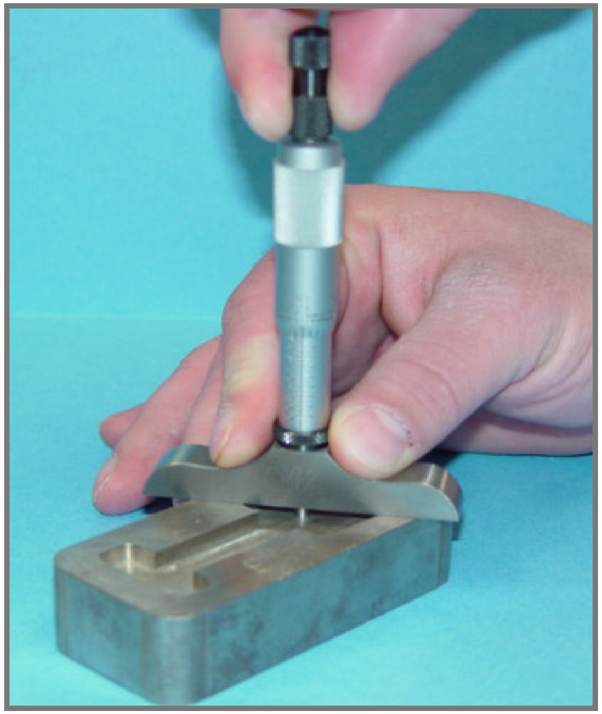
Dimensional Conformance of Welds



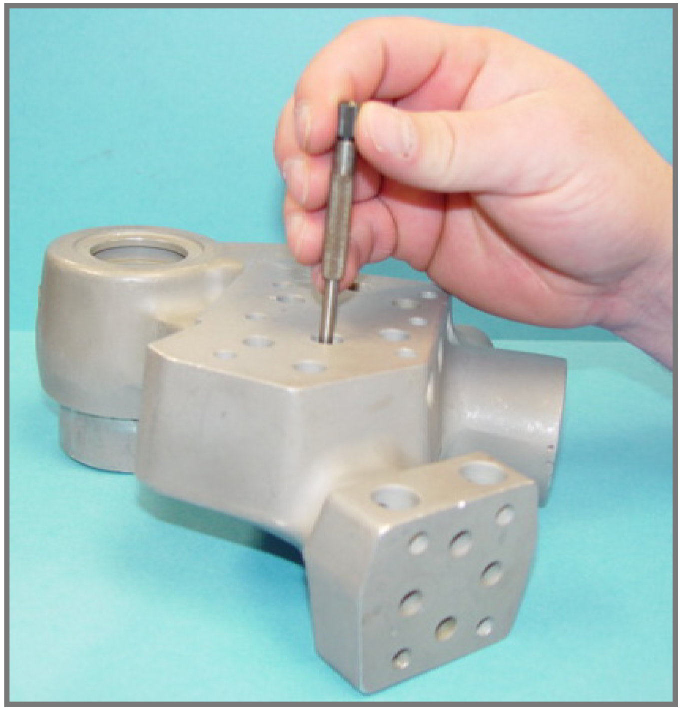


Measurement of undercut depth with VWAC gauge

Dimensional Conformance of Machined Parts



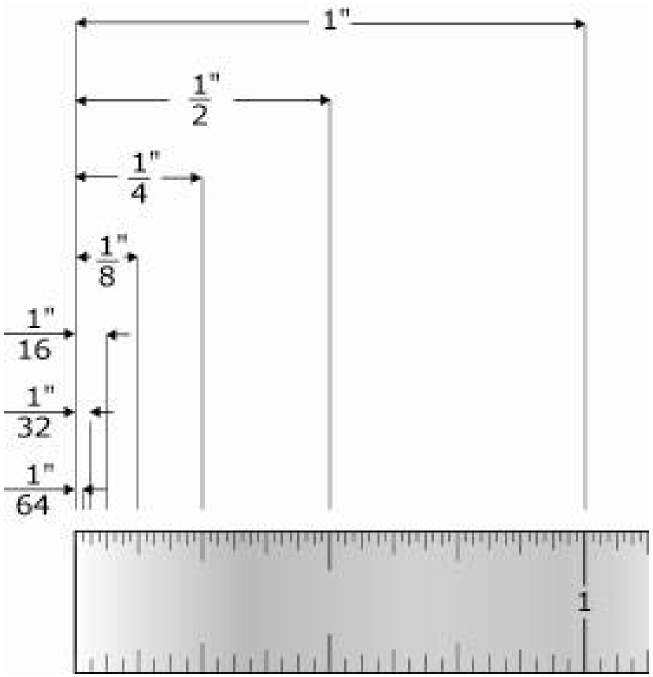
The finished depth of a machined mold is determined with a depth micrometer



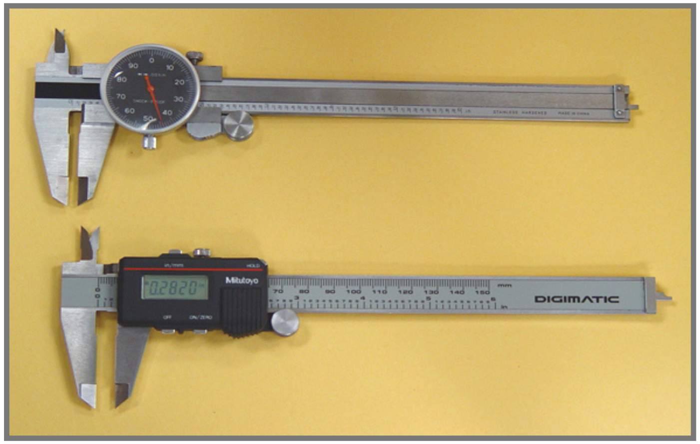
Small hole gauge used in determining hole diameter

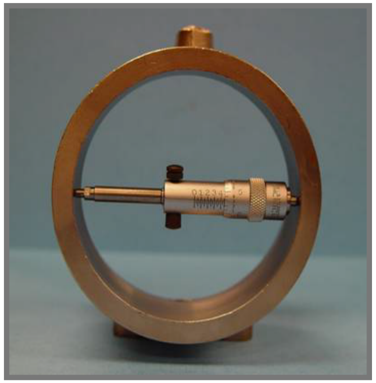
Basic Measurements

- One of the most common tools used in visual inspection is the rule or scale
- Used to measure linear dimensions, when properly used will measure within 0.015-in. or 1/64-in. and smaller
- Rules are made in a variety lengths, widths, and thicknesses
- They are graduated in common fractions, decimal units, and metric units, or combinations of both
- The specific type of rule is typically chosen relative to the application



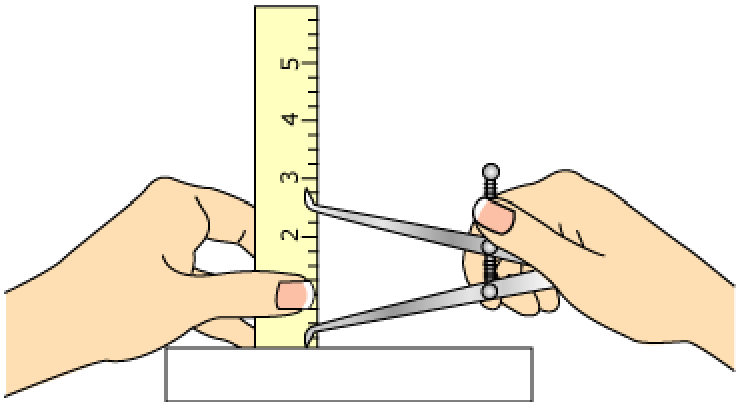
Precision Measurements

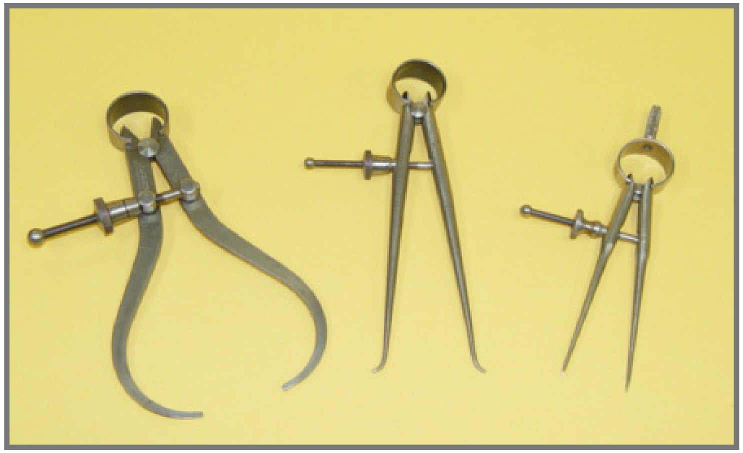




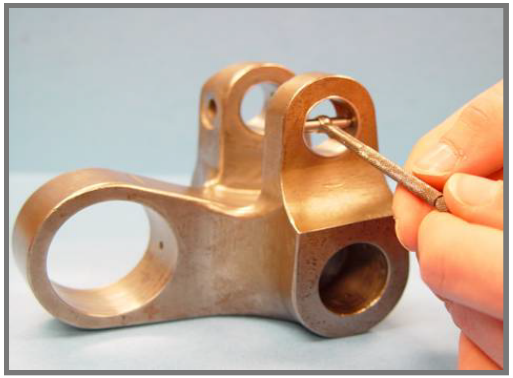
Transferring Gauges

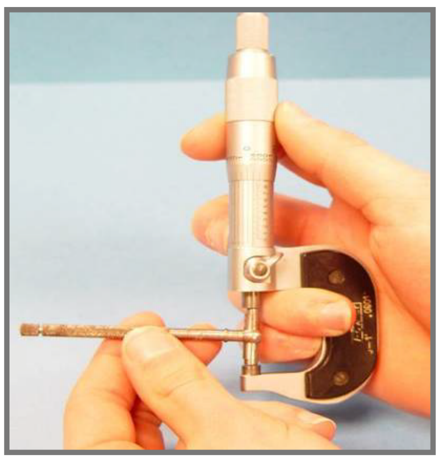
- Transfer instruments are used to take measurements which are transferred to direct measurement devices
- They consist of calipers, dividers, telescoping gauges and small hole gauges

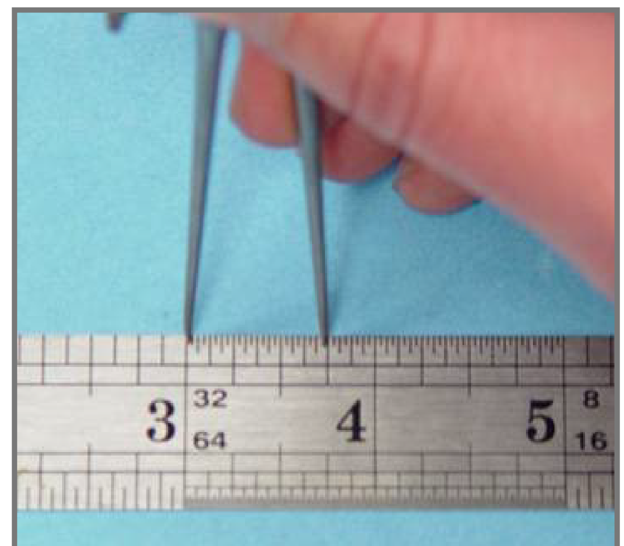




Transferring Gauges





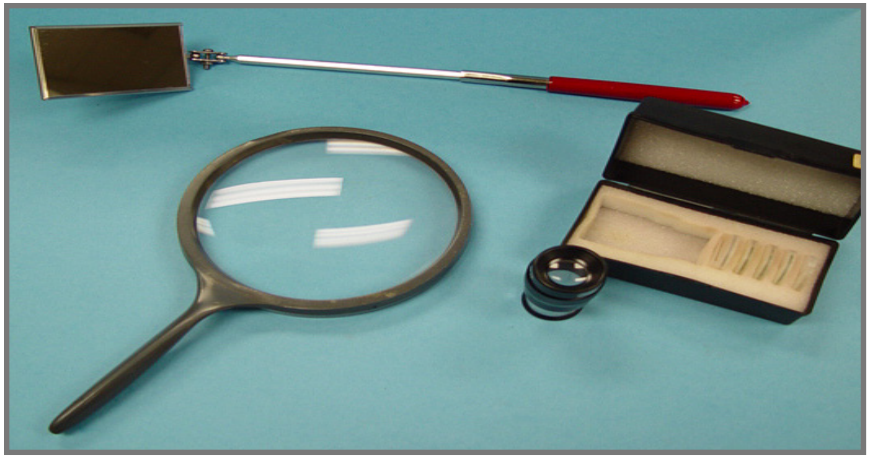


Direct and Remote Visual Inspection

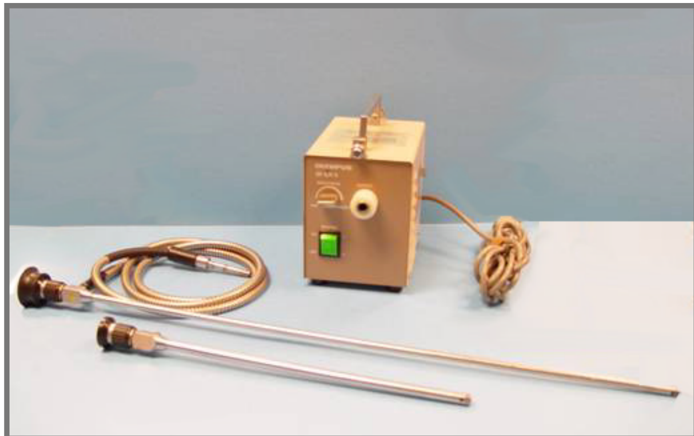
- Many codes refer to direct visual examination as a visual inspection
  - Requires that access to the area is sufficient to place the eye within 24 inches of the surface
  - Examined at an angle of not less than 30º to that surface
- If these requirements cannot be met, then remote visual inspection may be used
- Remote visual inspection may be accomplished with the use of a number of optical aids such as, mirrors, magnifiers, and rigid or flexible borescopes

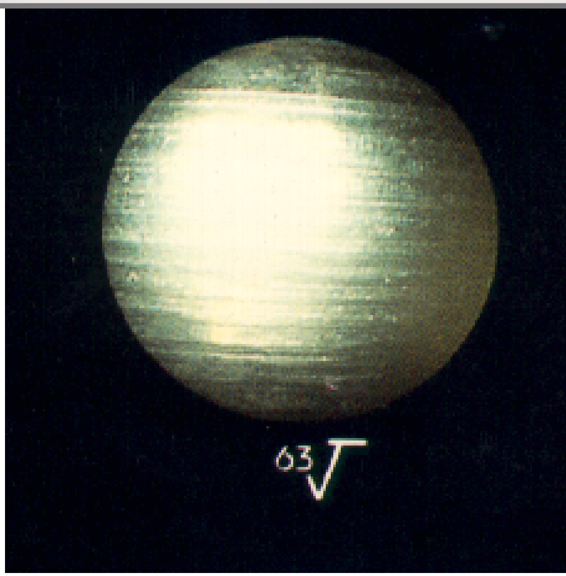
Optical Aids

- Mirrors are valuable aids in visual inspection; they allow the inspection of threaded and bored holes, inside surfaces of pipes and fittings, as well as many others
- Magnifiers assist by enlarging the size of the object being examined
  - Comparators are a magnifier with a measuring capability
    - The comparator has interchangeable reticles which provide measurements for threads, angles, linear measurement, diameters and radii

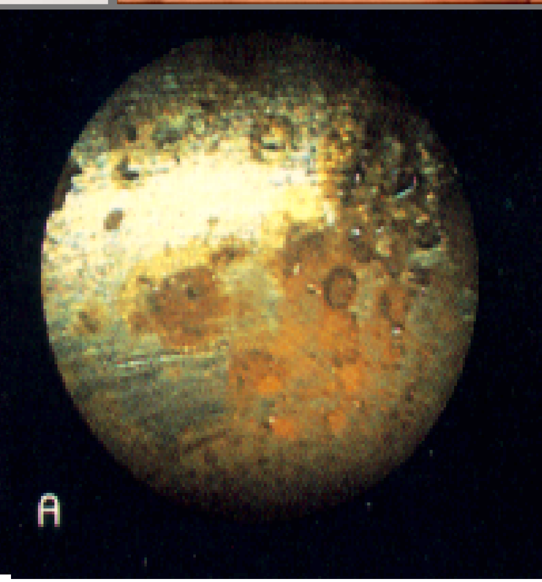


Optical Aids





Clean Surface



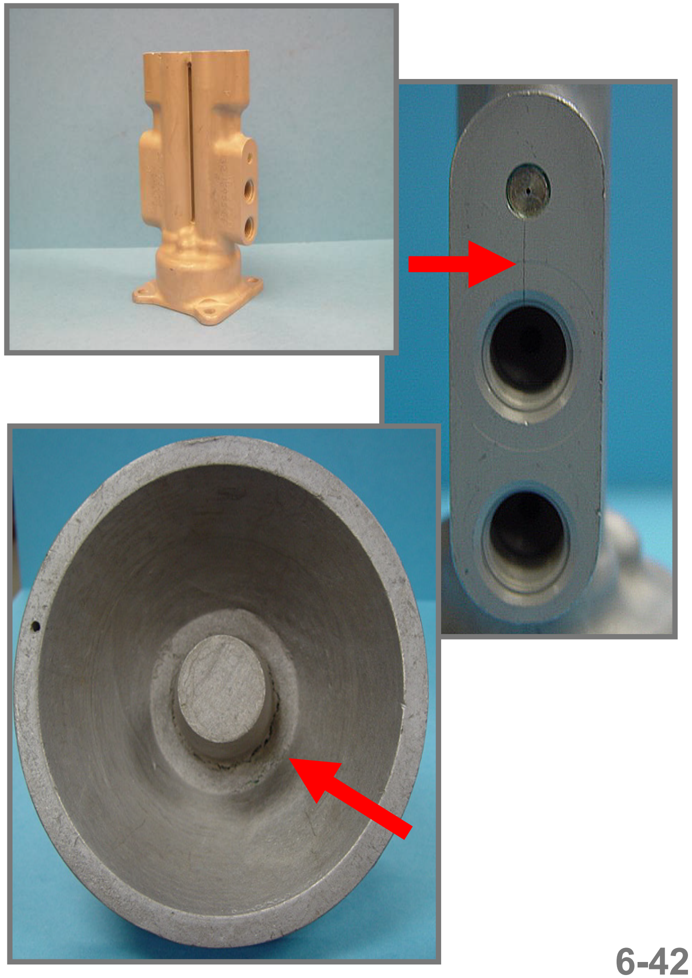
Corrosion Damage

Inspection Applications

- Applications for visual inspection range from looking a product over for obvious defect to performing detailed inspections
  - Detection of surface anomalies such as scratches, excess surface roughness, and areas void of paint or plating
  - Crack, porosity, corrosion or other flaw detection
  - Dimensional conformance
  - Precision measurements
  - Foreign object detection
  - Component location

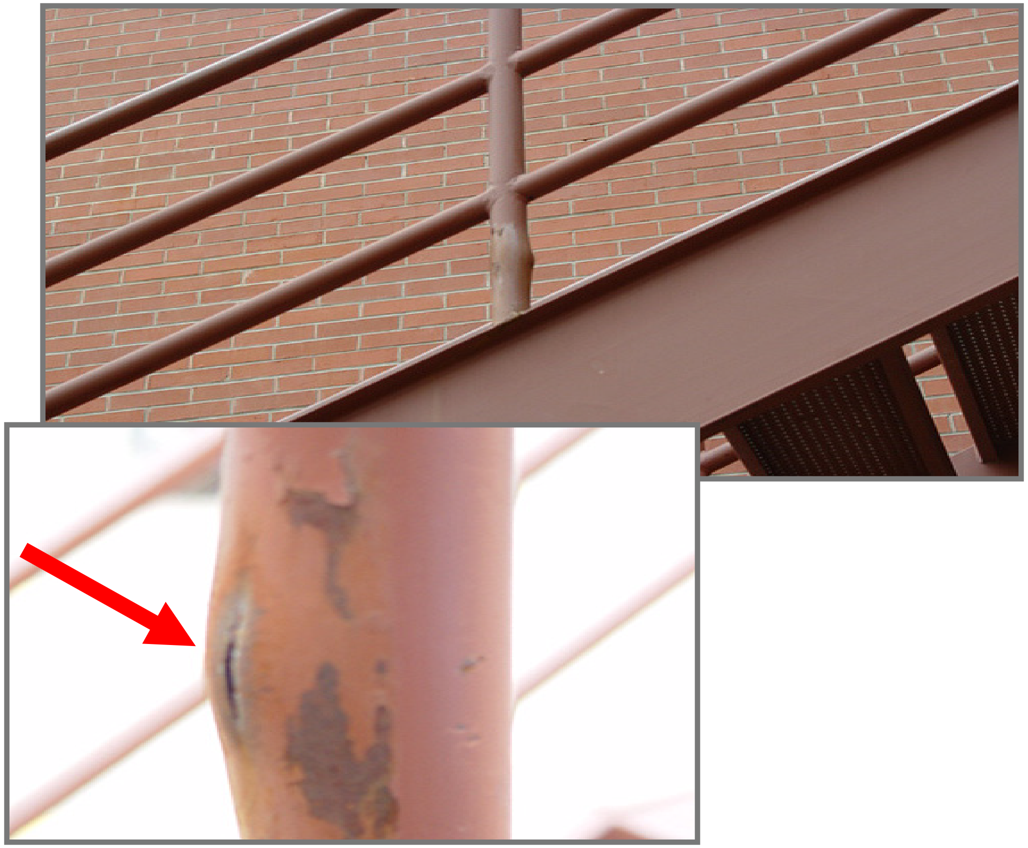
Flaw Detection

- Visual inspection of manufactured materials and components is a cost effective means of identifying flaws
- Visual inspection of a casting reveals a crack between a threaded opening and a pressed fit
- The aluminum sand casting has hot tears and shrinkage at the transition zones



Flaw Detection

- In-service inspections of existing components and structures is commonly accomplished visually
  - In this example, visual inspection of a fire escape reveals a failure in a handrail tube
  - The failure is in the tube seam and is likely the result of ice expansion

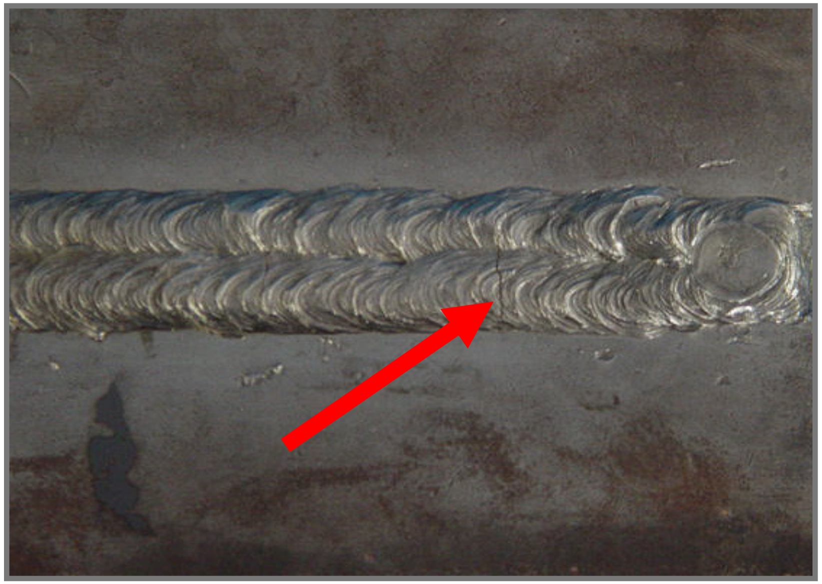


Flaw Detection

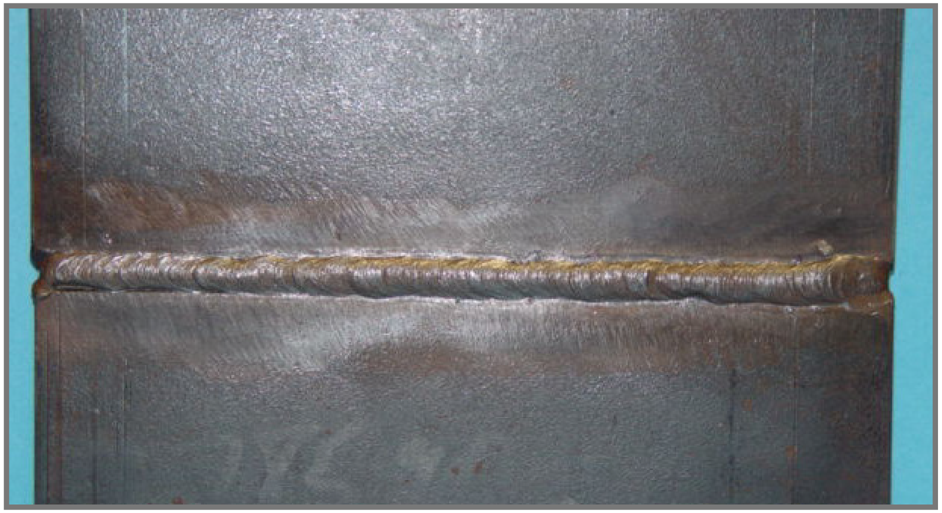
- Normal inspection practices for highway bridges rely almost entirely on visual inspection to evaluate the condition of the bridges
- Over 80 percent of all aircraft inspections are performed visually

Flaw Detection

- Weld quality requirements are commonly determined through visual inspection
- Many standards have established acceptance criteria for welds

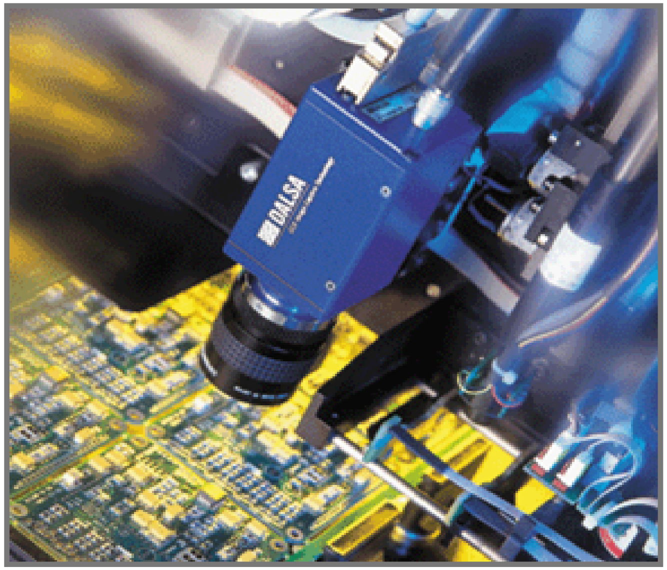


Transverse weld crack



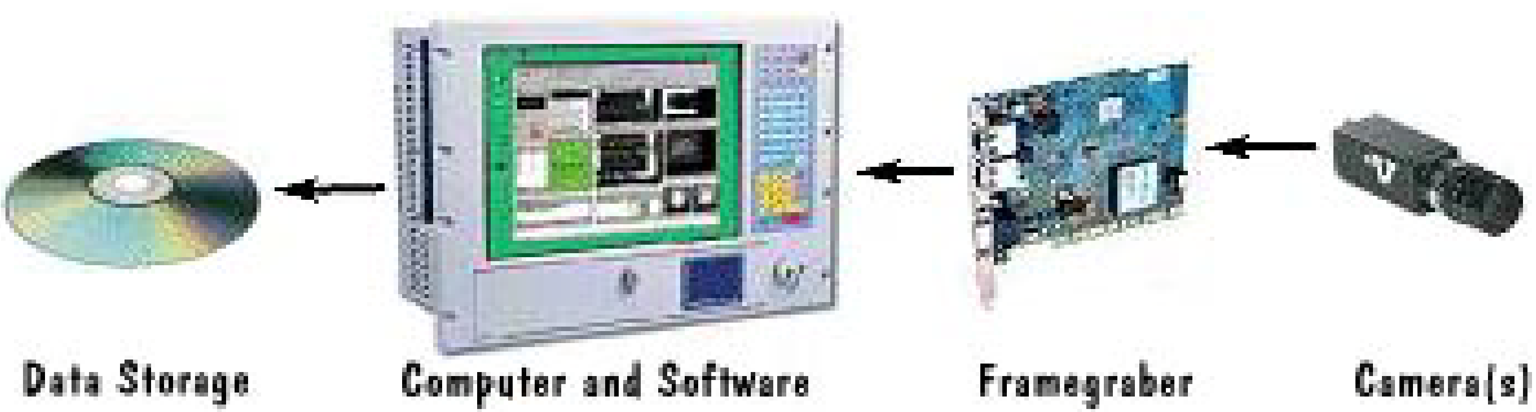
Slag rolled into toe of weld

Machine Vision Inspection



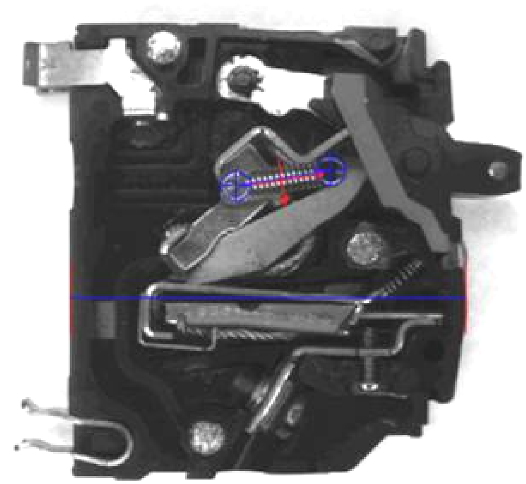
Machine Vision - Equipment

- Key System Elements
  - Common elements to all vision systems
    - Front-end optics
    - Frame grabber
    - Processor
    - Control software
  - Other components can be included in a machine vision system, which depend on the environment, the application, and the budget



Machine Vision – Applications

- Assembly verification
  - Caps, fasteners, electronic board components, etc.
- Surface inspection
  - Dents, scratches, porosity, etc.
- Verification of colors, gradients, patterns in fabrics and labels
- Confirmation of proper labeling for medications, foods and other products
- Inspection of coating coverage
- Feature measurements



Assembly Verification

Spark Gap Measurement

ASME Section V Requirements

- ASME Section V, Article 9, Visual Examination
  - T-920, General Requirements
    - Lists the requirements for written procedures, procedure qualifications and demonstration reference
      - Personnel requirements, physical requirements, equipment
  - T-950, Techniques
    - Describes different techniques used for visual inspection
      - T-952, Direct Visual Examination
      - T-953, Remote Visual Examination
      - T-954, Translucent Visual Examination
  - T-980, Evaluation
    - Covers the evaluation requirements and references the code of construction
      - ASME Section III or ASME B31.1
  - T-690, Documentation
    - Describes the minimum requirements for the examination record
      - Procedure and techniques used, examination personnel, map or record of indications, etc.

ASME Section V Requirements

Requirement (as applicable)	Essential Variable	Nonessential Variable
Change from direct to or from translucent	X	
Change from direct to remote	X	
Remote visual aids	X	
Personnel performance requirements, when required	X	
Lighting intensity (decrease only)	X	
Configurations to be examined and base material product forms (pipe, plate, forgings, etc.)		X
Lighting equipment		X
Methods or tools used for surface preparation		X
Equipment or devices used for a direct technique		X
Sequence of examination		X
Personnel qualifications		X

ASME Acceptance Requirements for Visual Inspection

- ASME B31.1
  - Section 136.4.2 provides visual examination acceptance criteria
  - References ASME Section V, Article 9
- ASME Section III, Division 1 – NB only gives visual acceptance criteria for brazed joints

Indication	ASME B31.1 Acceptance Criteria
External Cracks	Unacceptable
External Undercut	Greater than 1/32 in. deep
Weld Reinforcement	Maximum limit ranges from 1/16 in. through 1/4 in. (depends on material thickness and design temperature)
External Lack of Fusion	Unacceptable
Incomplete Penetration	Unacceptable
Linear Indication	Greater than 3/16 in.
Surface Porosity	Any single indication greater than 3/16 in.
	Four or more indications separated by 1/16 in or less edge to edge

Visual Inspection Summary

- Advantages
  - Readily used on almost all materials
  - Simple to perform
  - Low in cost, (application dependent)
  - Relatively quick
  - Results may be permanently recorded.
  - Can be automated
- Disadvantages
  - Direct inspections are limited to surfaces only
  - Indirect inspections require greater inspector knowledge and training
  - Inspector dependent, knowledge of materials and processing, eye sight
  - Standards (workmanship) may be difficult to obtain

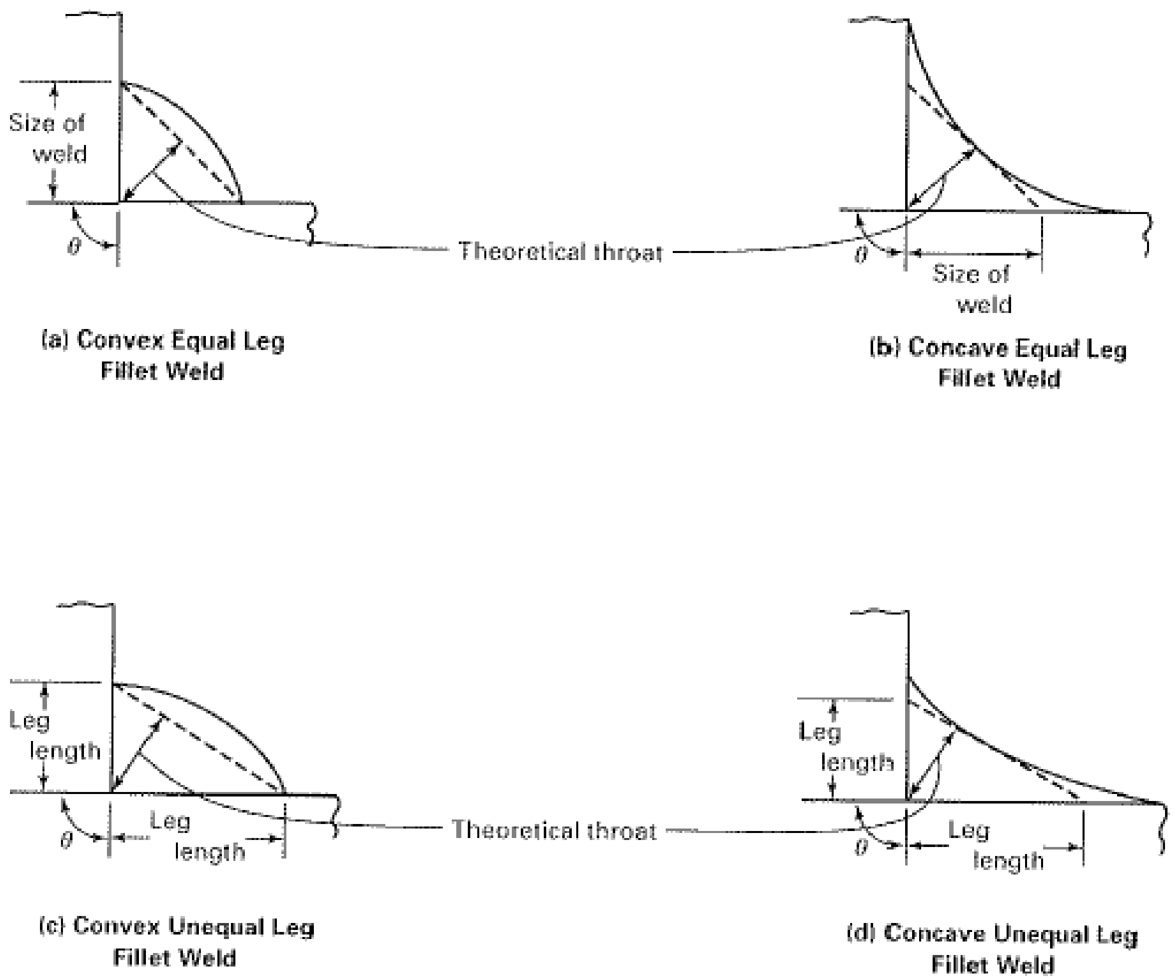
Visual Inspection Experience

- Is the fillet weld visually acceptable according to ASME B31.1?

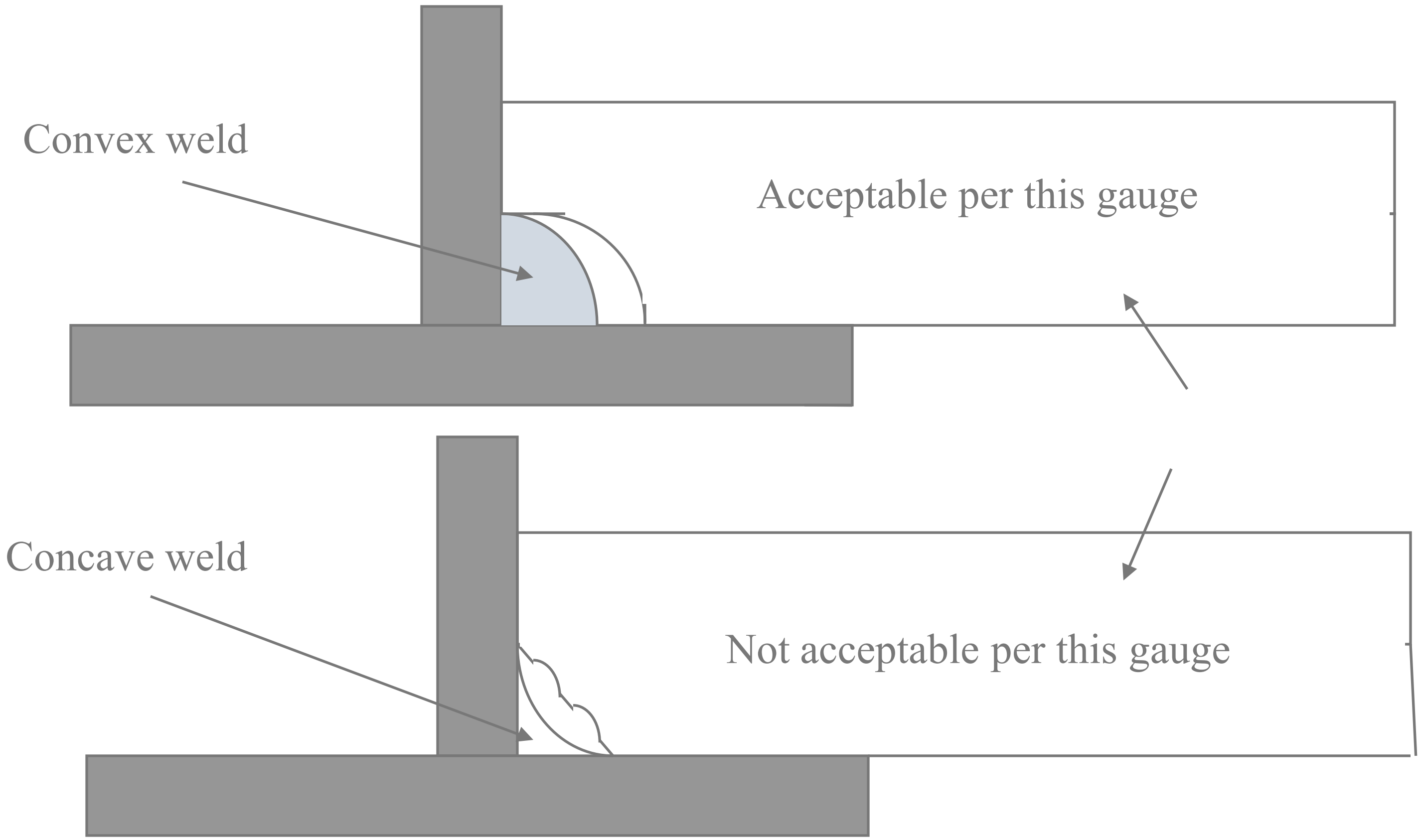
Indication	ASME B31.1 Acceptance Criteria
External Cracks	Unacceptable
External Undercut	Greater than 1/32-in. deep
Weld Reinforcement	Maximum thickness 3/32-in.
External Lack of Fusion	Unacceptable
Incomplete Penetration	Unacceptable
Linear Indication	Greater than 3/16-in.
Surface Porosity	Any single indication greater than 3/16-in.
	Four or more indications separated by 1/16-in. or less edge to edge

Visual Inspection Experience

Fig. 127.4.4(A) Fillet Weld Size



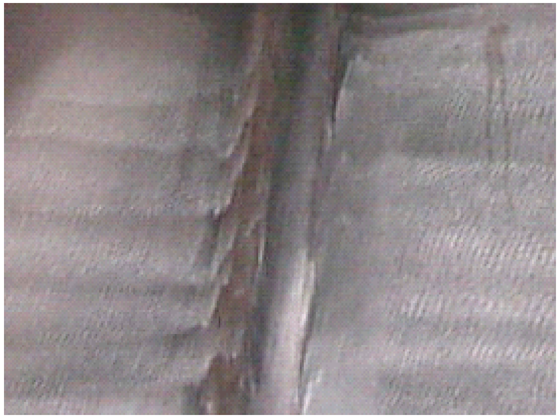
Visual Inspection Experience

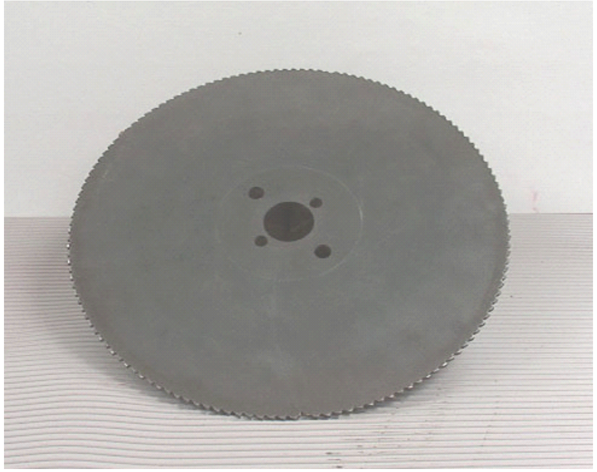


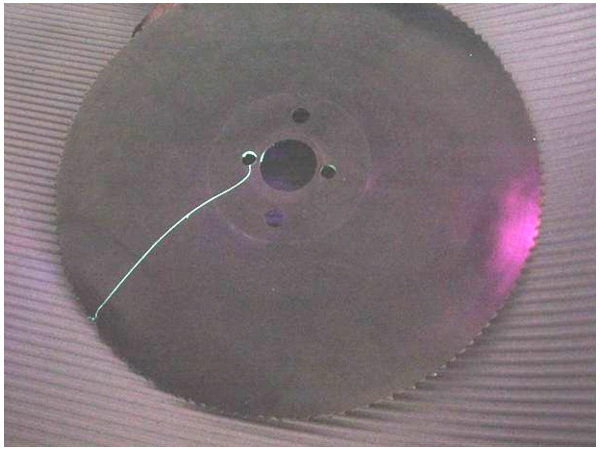
Liquid Penetrant Testing

Module 6A.2

Examples of Liquid Penetrant Testing

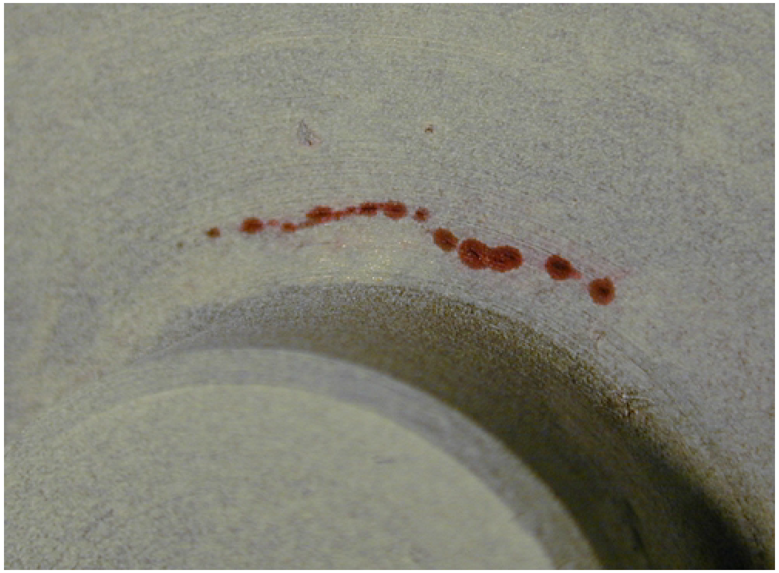






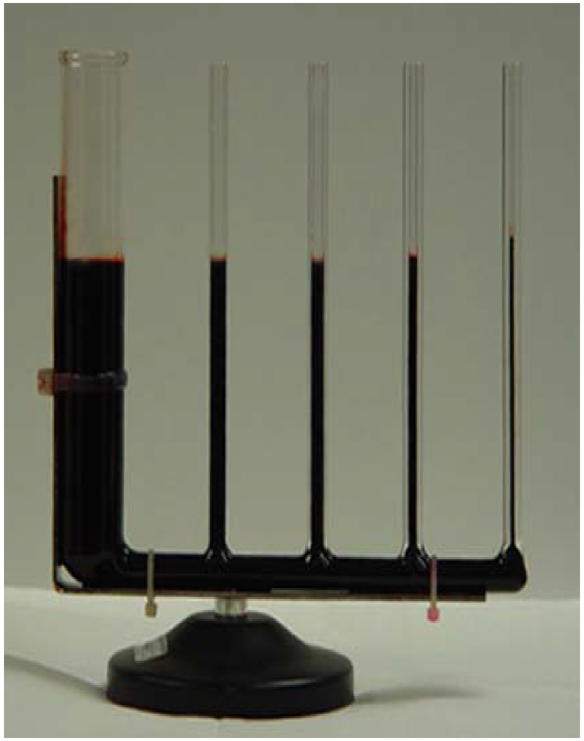
How Does PT Work?

- A liquid with high surface wetting characteristics is applied to the surface of a component under test
- The penetrant “penetrates” into surface breaking discontinuities via capillary action and other mechanisms
- Excess penetrant is removed from the surface and a developer is applied to pull trapped penetrant back to the surface
- With good inspection technique, visual indications of surface discontinuities present become apparent



What Makes PT Work?

- Every step of the penetrant process is done to promote capillary action
- This is the phenomenon of a liquid rising or climbing when confined to small openings due to surface wetting properties of the liquid
  - Plants and trees draw water up from the ground to their branches and leaves to supply their nourishment
  - The human body has miles of capillaries that carry life sustaining blood to our entire body

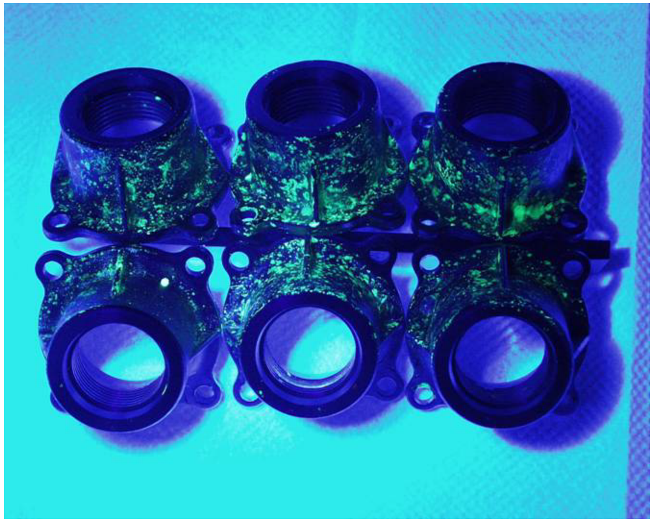


What Can Be Inspected Via PT?

- Almost any material that has a relatively smooth, non-porous surface on which discontinuities or defects are suspected

What Cannot be Inspected Via PT?

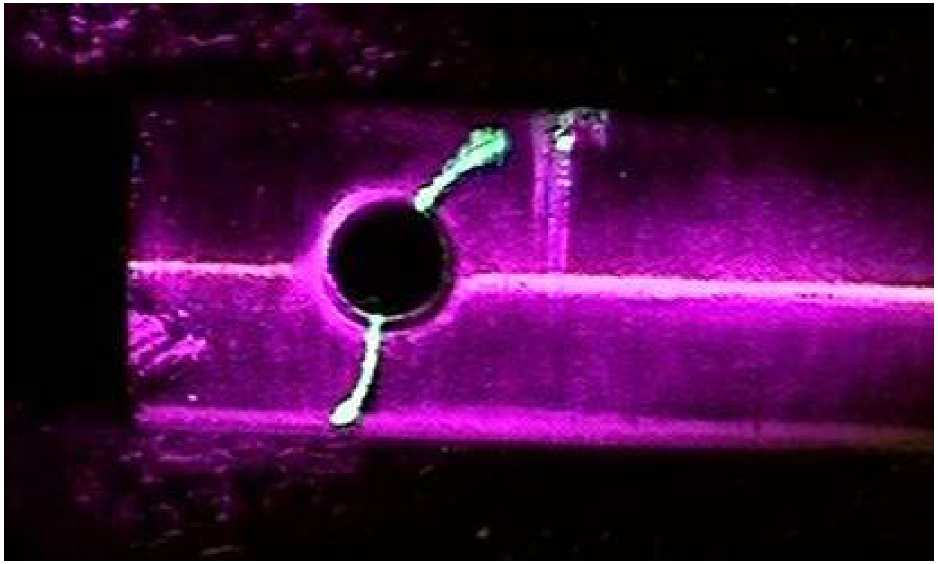
- Components with rough surfaces, such as sand castings, that trap and hold penetrant
- Porous ceramics
- Wood and other fibrous materials
- Plastic parts that absorb or react with the penetrant materials
- Components with coatings that prevent penetrants from entering defects

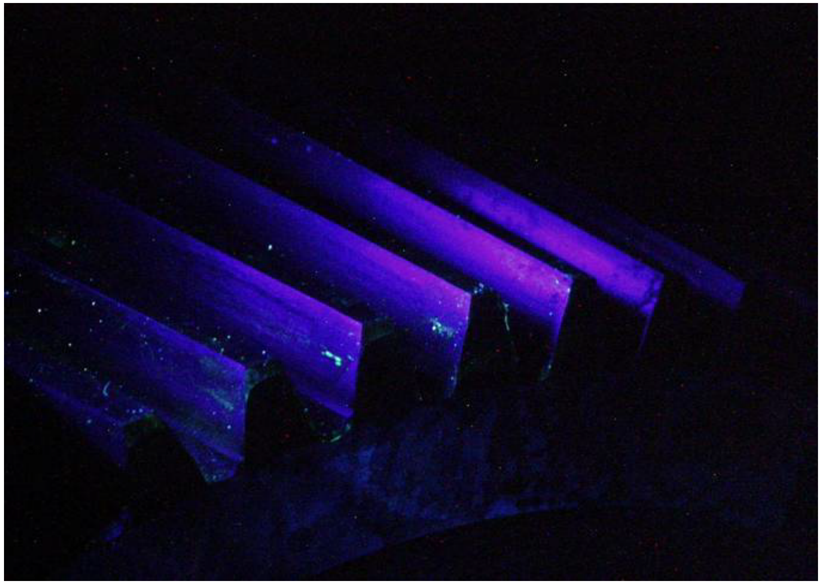


Defect indications become less distinguishable as the background "noise" level increases

What Types of Discontinuities Can Be Detected Via PT?

- All defects that are open to the surface
  - Rolled products – Cracks, seams, laminations
  - Castings – Cold shuts, hot tears, porosity, blow holes, shrinkage
  - Forgings – Cracks, laps, external bursts
  - Welds – Cracks, porosity, undercut, overlap, lack of fusion, lack of penetration





Choices of Penetrant Materials

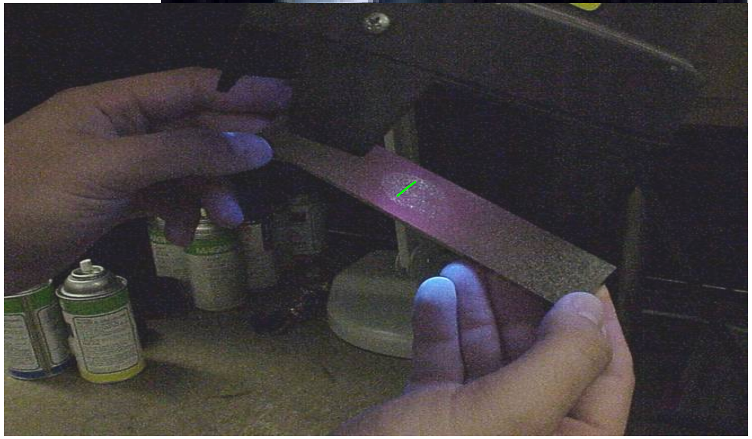
Penetrant	
Types	Flourescent
	Visible
Method	Water Washable
	Postemulsifiable – Lipophilic
	Solvent Removable
	Postemulsifiable - Hydrophilic
Developer	
Form	Dry Powder
	Wet, Water Soluble
	Wet, Water Suspendable
	Wet, Non-Aqueous

Sensitivity Levels

- Penetrants are also formulated to produce a variety of sensitivity levels
  - The higher the sensitivity level, the smaller the defect that the penetrant system is capable of detecting
- The four sensitivity levels are:
  - Level 4 - Ultra-High Sensitivity
  - Level 3 - High Sensitivity
  - Level 2 - Medium Sensitivity
  - Level 1 - Low Sensitivity
- As the sensitivity level increases, so does the number of nonrelevent indications
  - Penetrant needs to be selected that will find the defects of interest but not produce too many nonrelevent indications.

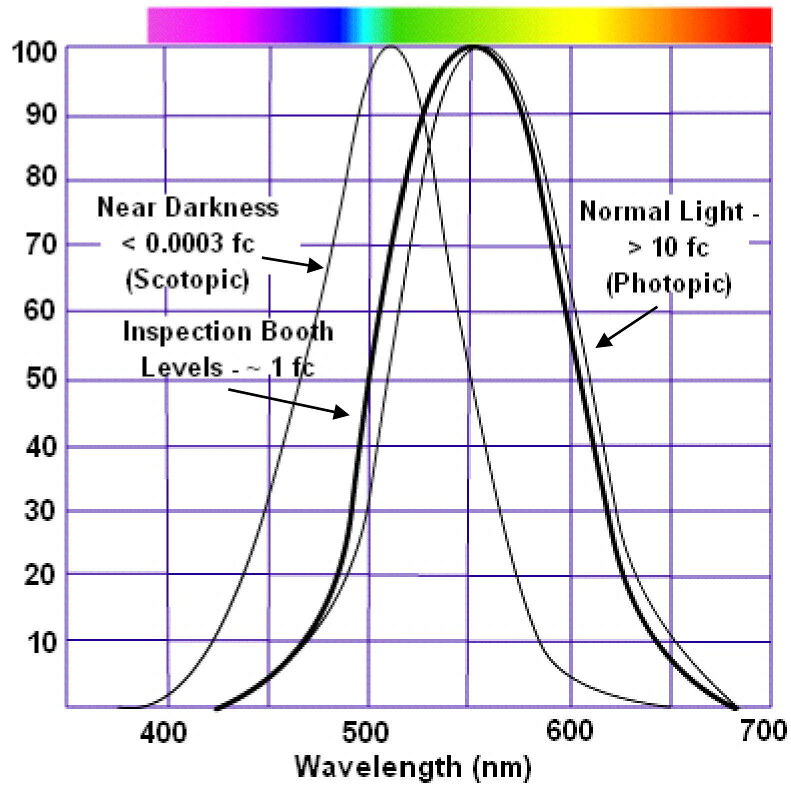
Visible vs. Fluorescent PT

- Inspection can be performed using visible (or red dye) or fluorescent penetrant materials
- Visible PT is performed under white light while fluorescent PT must be performed using an ultraviolet light in a darkened area
- Fluorescent PT is more sensitive than visible PT because the eye is more sensitive to a bright indication on a dark background
  - Sensitivity ranges from 1 to 4



Why is Visible Penetrant Red and Fluorescent Penetrant Green?

- Visible penetrant is usually red because red stands out and provides a high level of contrast against a light background
- Fluorescent penetrant is green because the eye is most sensitive to the color green

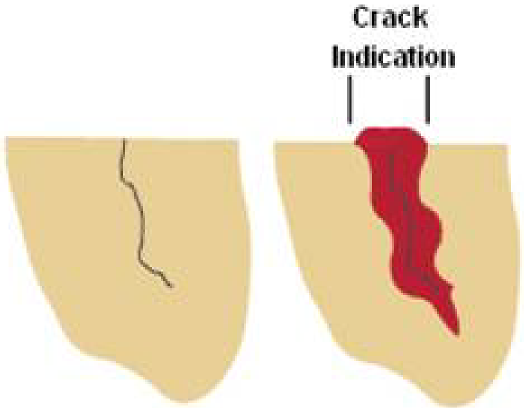


Penetrant Removal Method

- Penetrants are also classified by the method of removing the excess penetrant
  - Solvent removable
  - Water washable
  - Post-emulsifiable

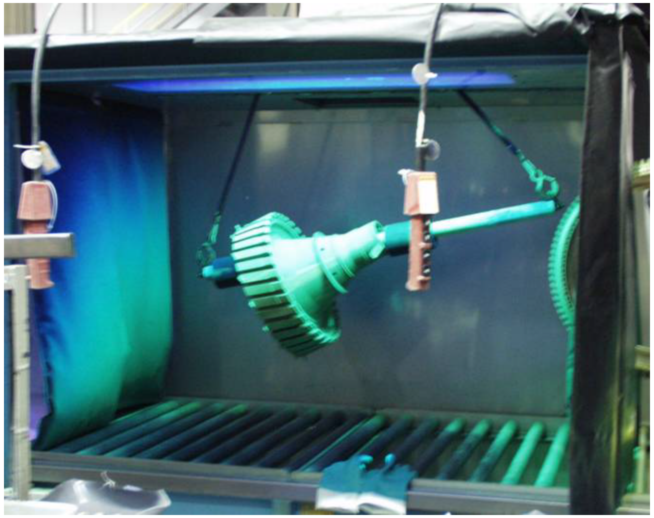
Developers

- The role of the developer is to pull trapped penetrant out of defects and to spread it out on the surface so it can be seen Also provides a light background to increase contrast when visible penetrant is used



6 Steps of Penetrant Testing

- 1. Pre-Clean
- 2. Penetrant Application
- 3. Excess Penetrant Removal
- 4. Developer Application
- 5. Inspect/Evaluate
- 6. Post-clean

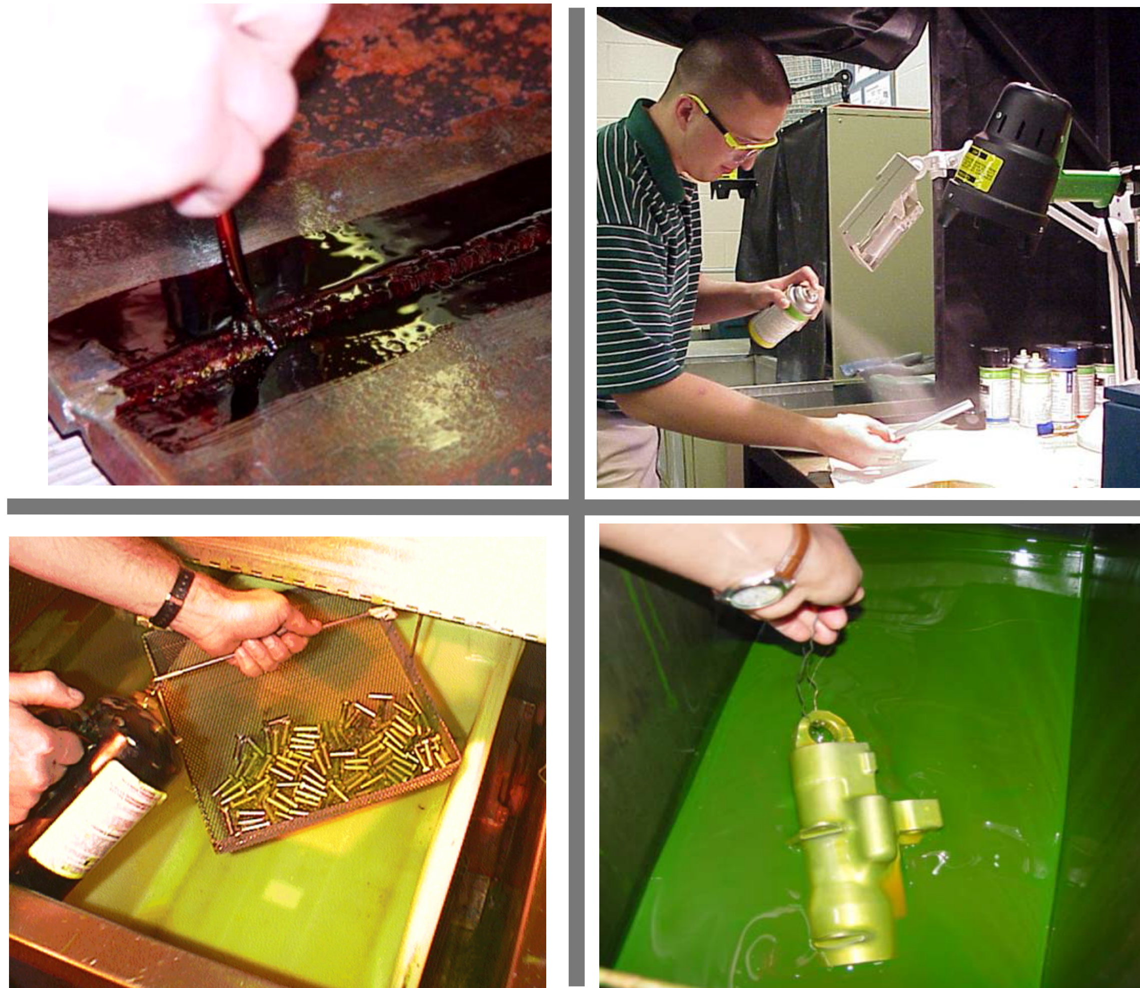


Pre-Cleaning – Step 1

- Parts must be free of dirt, rust, scale, oil, grease, etc. to perform a reliable inspection
- The cleaning process must remove contaminants from the surfaces of the part and defects, and must not plug any of the defects
- **Pre-cleaning is the most important step in the PT process!!!**

Penetrant Application – Step 2

- There are many methods of application
  - Brushing
  - Spraying
  - Dipping/Immersing
  - Flow-on
  - And more

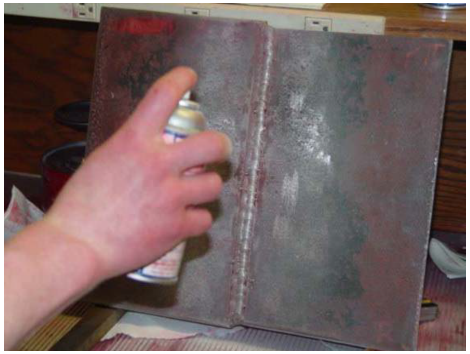


Excess Penetrant Removal – Step 3

- The removal technique depends upon the type of penetrant used, as stated earlier
  - Solvent Removable
  - Water Washable
  - Post Emulsifiable

Developer Application – Step 4

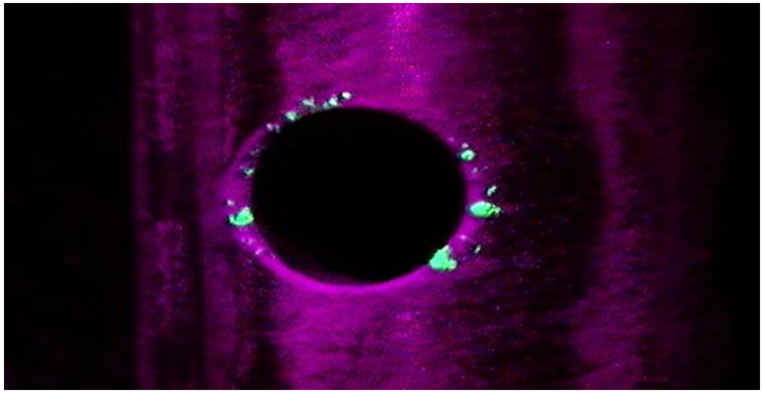
- The method of developer application is dependent on the type of developer used
- The primary methods for the main developer types will be covered in the following slides
    - Dry
    - Wet
    - Nonaqueous Wet




Inspection/Evaluation – Step 5

- In this step the inspector evaluates the penetrant indications against specified accept/reject criteria and attempts to determine the origin of the indication
- The indications are judged to be either relevant, non-relevant, or false

Non-relevant weld geometry indications



Relevant crack indications from an abusive drilling process

Post Clean – Step 6

- The final step in the penetrant inspection process is to thoroughly clean the part that has been tested to remove all penetrant processing materials
- The residual materials could possibly affect the performance of the part or affect its visual appeal

Penetrant Inspection Systems

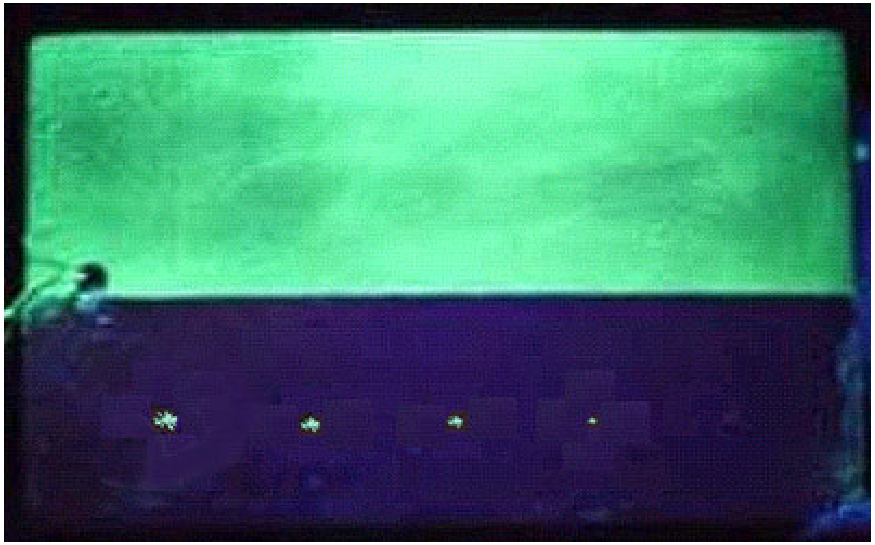
Penetrant systems can be highly portable or stationary.

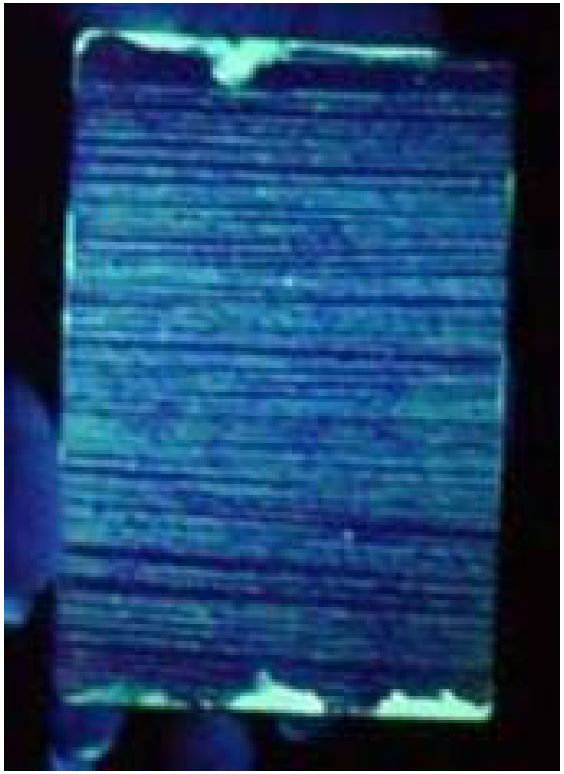
Portable Penetrant System

Stationary Penetrant System

Verification of Penetrant System Performance

- Since penetrant testing involves multiple processing steps, the performance of the materials and the processes should be routinely checked using performance verification tools
  - TAM Panels
  - Crack Sensitivity Panels
  - Run Check Panels





ASME Section V Requirements

- ASME Section V, Article 6, Liquid Penetrant Testing
  - T-620, General Requirements
    - Lists the requirements for written procedures and procedure qualifications
  - T-640, Miscellaneous Requirements
    - Include requirements for control of contaminants, surface preparation and drying after preparation
  - T-650, Techniques
    - Describes different techniques used for liquid penetrant testing
      - Visible or flourescent
      - Water washable, post-emulsifiying, or solvent removable
      - Inspecting at nonstandard temperatures
  - T-660, Calibration
    - Covers the calibration requirements of the testing equipment

ASME Section V Requirements

Requirement (as applicable)	Essential Variable	Nonessential Variable
Identification of and any change in type or family group of penetrant materials including developers, emulsifiers, etc.	X	
Surface preparation (finishing and cleaning, including type of cleaning solvent)	X	
Method of applying penetrant	X	
Method of removing excess surface penetrant	X	
Hydrophilic or lipophilic emulsifier concentration and dwell time in dip tanks and agitation time for hydrophilic emulsifiers	X	
Hydrophilic emulsifiers concentration in spray applications	X	
Method of applying developer	X	
Minimum and maximum time periods between steps and drying aids	X	
Decrease in penetrant dwell time	X	
Increase in developer dwell time (Interpretation Time)	X	

ASME Section V Requirements

Requirement (as applicable)	Essential Variable	Nonessential Variable
Minimum light intensity	X	
Surface temperature outside 40ºF to 125ºF (5ºC to 52ºC) or as previously qualified	X	
Performance demonstration, when required	X	
Personnel qualification requirements		X
Materials, shapes, or sizes to be examined and the extent of examination		X
Post-examination cleaning technique		X

ASME Section V Requirements

- ASME Section V, Article 6, Liquid Penetrant Testing
  - T-670, Examination
    - Lists the examination steps
      - T-671, Penetrant Application
      - T-672, Penetrant (Dwell) Time
      - T-673, Excess Penetrant Removal
      - T-675, Developing
      - T-676, Interpretation
      - T-677, Post-Examination cleaning

TABLE T-672 MINIMUM DWELL TIMES

Material	Form	Type of Discontinuity	Dwell Times [Note (1)] (minutes)	
			Penetrant	Developer
Aluminum, magnesium, steel, brass and bronze, titanium and high-temperature alloys	Castings and welds	Cold shuts, porosity, lack of fusion, cracks (all forms)	5	10
	Wrought materials — extrusions, forgings, plate	Laps, cracks (all forms)	10	10
Carbide-tipped tools	. . .	Lack of fusion, porosity, cracks	5	10
Plastic	All forms	Cracks	5	10
Glass	All forms	Cracks	5	10
Ceramic	All forms	Cracks	5	10

NOTE:
(1) For temperature range from 50°F to 125°F (10°C to 52°C). For temperatures from 40°F (5°C) up to 50°F (10°C), minimum penetrant dwell time shall be 2 times the value listed.

ASME Section V Requirements

- ASME Section V, Article 6, Liquid Penetrant Testing
  - T-680, Evaluation
    - Covers the evaluation requirements and references the code of construction
      - ASME Section III or ASME B31.1
  - T-690, Documentation
    - Defines what are considered rejectable and non-rejectable indications and describes the minimum requirements for the examination record
      - Procedure used
      - Liquid penetrant type and other equipment used
      - Examination personnel
      - Map or record of indications
      - Material and thickness
      - Date of examination

ASME Section III – NB and B31.1 Acceptance Requirements for Liquid Penetrant Testing

- Section NB-5350 of ASME Section III provides liquid penetrant examination acceptance criteria
- Section 136.4.4 of ASME B31.1 provides liquid penetrant examination acceptance criteria
- Both standards references ASME Section V, Article 6

Criteria	ASME Section III – NB	ASME B31.1
Crack or Linear Indication	Unacceptable	
Rounded Indications	Any single indication greater than 3/16-in.	
	Four or more indications in a line separated by 1/16-in or less edge to edge	
	Ten or more indications in any 6-in^2 of surface	

Advantages of Liquid Penetrant Testing

- Relative ease of use
- Can be used on a wide range of material types
- Large areas or large volumes of parts/materials can be inspected rapidly and at low cost
- Parts with complex geometries are routinely inspected
- Indications are produced directly on surface of the part providing a visual image of the discontinuity
- Initial equipment investment is low
- Portable

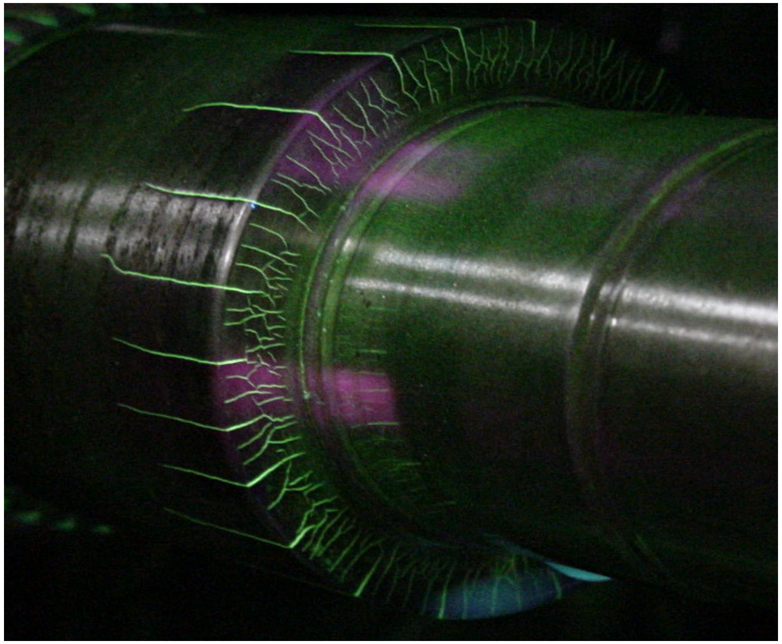
Limitations of Liquid Penetrant Testing

- Only detects surface breaking defects
- Requires relatively smooth, nonporous material
- Precleaning is critical
  - Contaminants can mask defects
- Requires multiple operations under controlled conditions
- Chemical handling precautions necessary (toxicity, fire, waste)
- Metal smearing from machining, grinding and other operations inhibits detection
  - Materials may need to be etched prior to inspection
- Post cleaning is necessary to remove chemicals

Magnetic Particle Testing

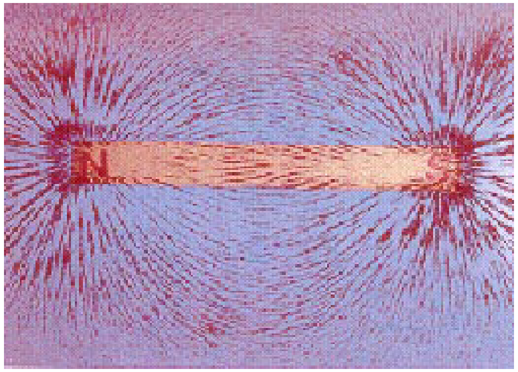
Module 6A.3

Examples of Magnetic Particle Testing

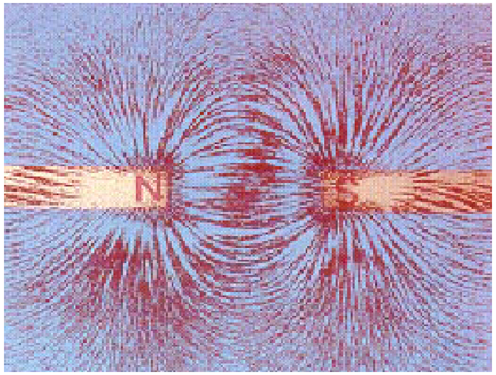


Introduction to Magnetism

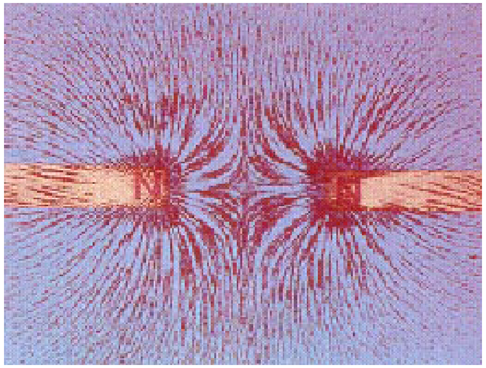
- Magnetism is the ability of matter to attract other matter to itself
  - Magnetic lines of force can be found in and around the objects
  - A magnetic pole is a point where a magnetic line of force exits or enters a material



Magnetic lines of force around a bar magnet



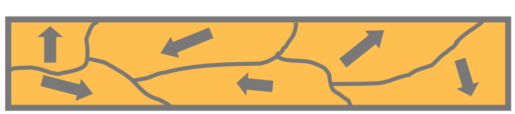
Opposite poles attracting

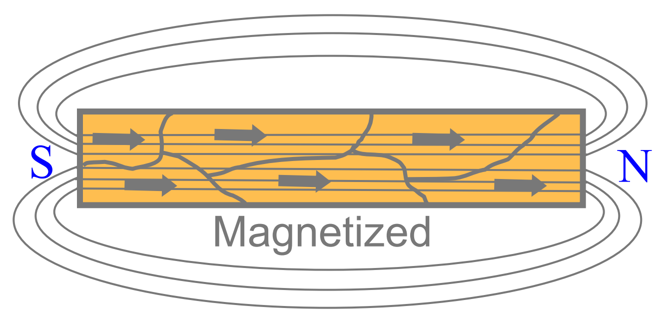


Similar poles repelling

Ferromagnetic Materials

- A material is considered ferromagnetic if it can be magnetized
  - Materials with a significant iron (Fe), nickel (Ni), or cobalt (Co) content are generally ferromagnetic
- Ferromagnetic materials are made up of many regions (i.e., magnetic domains) in which the magnetic fields of atoms are aligned
- Magnetic domains point randomly in demagnetized material, but can be aligned using electrical current or an external magnetic field to magnetize the material

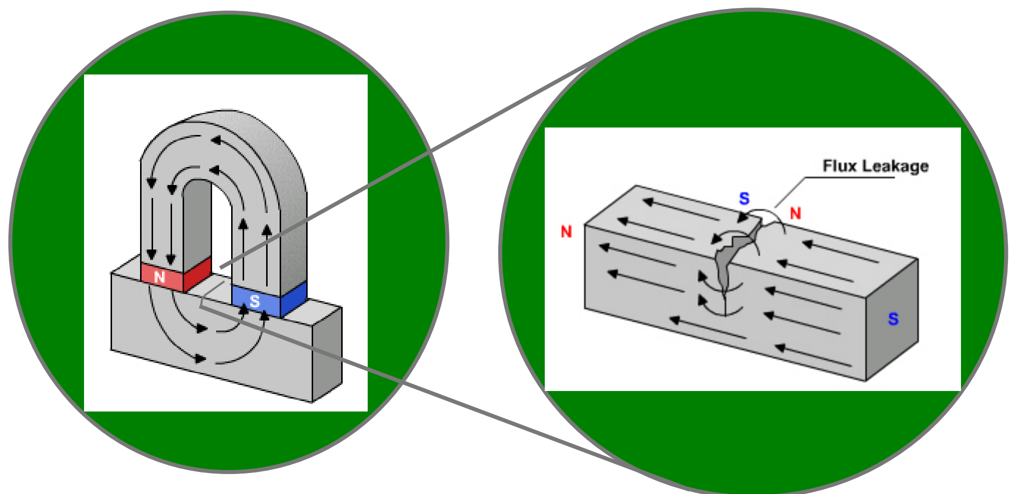

Demagnetized

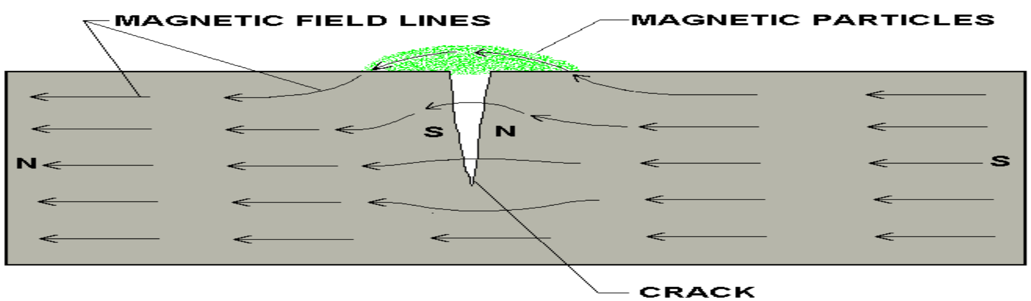


Magnetized

How Does MT Work?

- A ferromagnetic test specimen is magnetized with a strong magnetic field created by a magnet or special equipment
- If the specimen has a discontinuity, the discontinuity will interrupt the magnetic field flowing through the specimen and a leakage field will occur





Basic Procedure

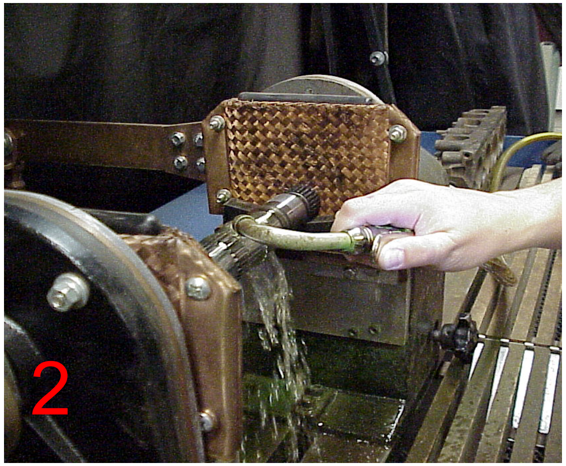
- There are four basic steps in a magnetic particle testing procedure
  - Component pre-cleaning
  - Introduction of magnetic field
  - Application of magnetic media
  - Interpretation of magnetic particle indications

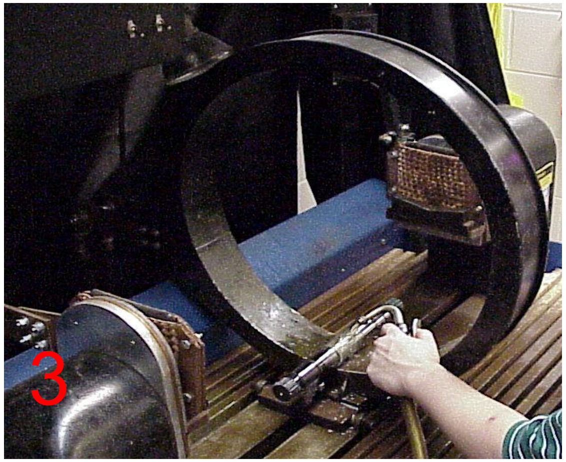
Pre-Cleaning

- When inspecting a test part via MT, it is essential for the particles to have an unimpeded path for migration to both strong and weak leakage fields alike
- The part's surface should be clean and dry before inspection
- Contaminants such as oil, grease, or scale may not only prevent particles from being attracted to leakage fields, they may also interfere with interpretation of indications

Introduction of the Magnetic Field

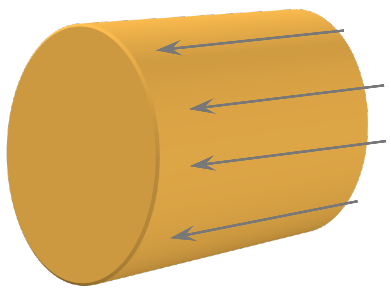
- The required magnetic field can be introduced into a component in a number of different ways
  - Using a permanent magnet or an electromagnet that contacts the test piece
  - Flowing an electrical current through the specimen
  - Flowing an electrical current through a coil of wire around the part or through a central conductor running near the part

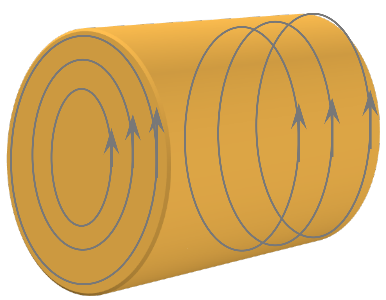




Direction of the Magnetic Field

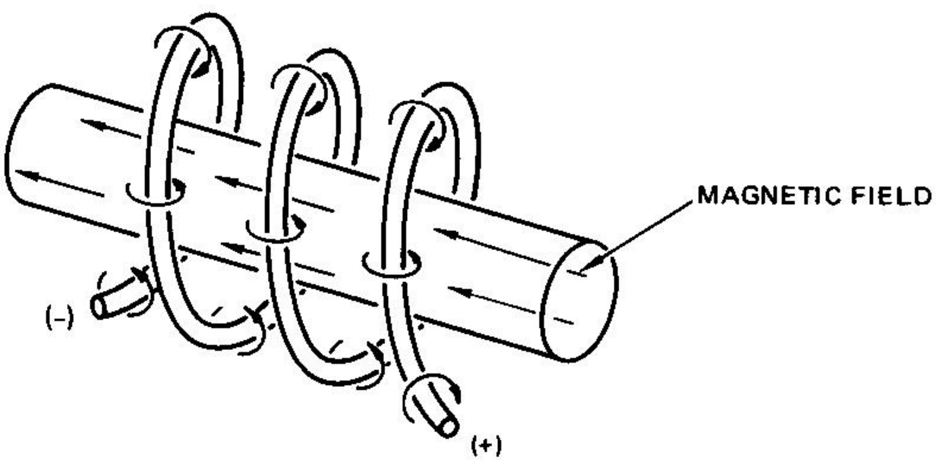
- Two general types of magnetic fields may be established within the specimen
- The type of magnetic field established is determined by the method used to magnetize the specimen
  - Longitudinal magnetic field - magnetic lines of force run parallel to the long axis of the part
  - Circular magnetic field - magnetic lines of force run circumferentially around the perimeter of the part





Producing a Longitudinal Magnetic Field Using a Coil

- A longitudinal magnetic field is usually established by placing the part near the inside or a coil's annulus
- This produces magnetic lines of force that are parallel to the long axis of the test part.

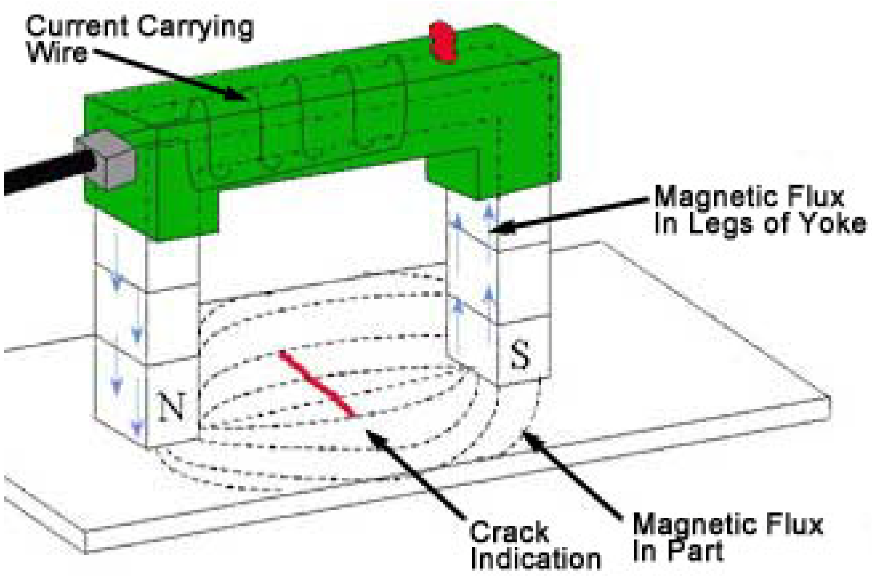


Coil on Wet Horizontal Inspection Unit

Portable Coil

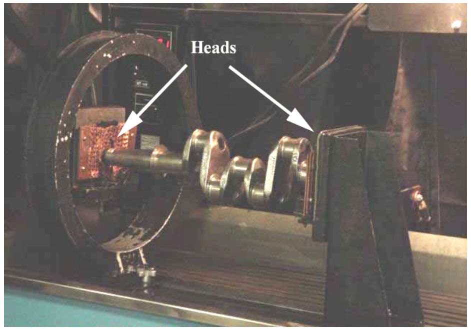
Producing a Longitudinal Field Using Permanent or Electromagnetic Magnets

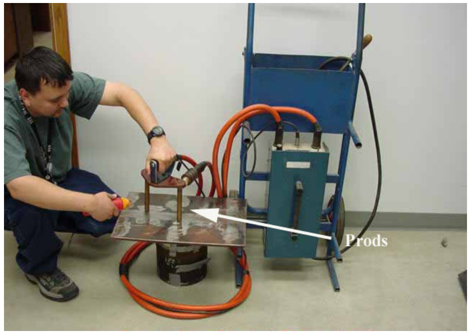
- Permanent magnets and electromagnetic yokes are often used to produce a longitudinal magnetic field
- The magnetic lines of force run from one pole to the other, and the poles are positioned such that **any flaws present run normal to these lines of force**

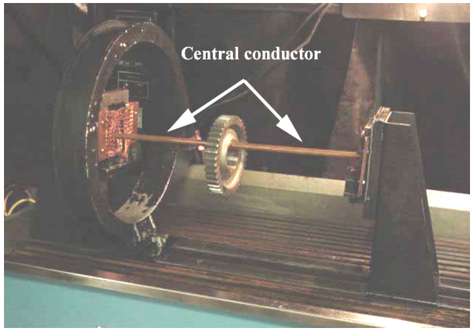


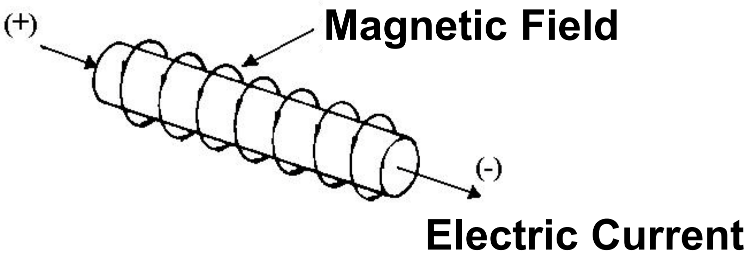
Circular Magnetic Fields

- Circular magnetic fields are produced by passing current through the part or by placing the part in a strong circular magnet field
- A headshot on a wet horizontal test unit and the use of prods are several common methods of injecting current in a part to produce a circular magnetic field
- Placing parts on a central conductor carrying high current is another way to produce the field



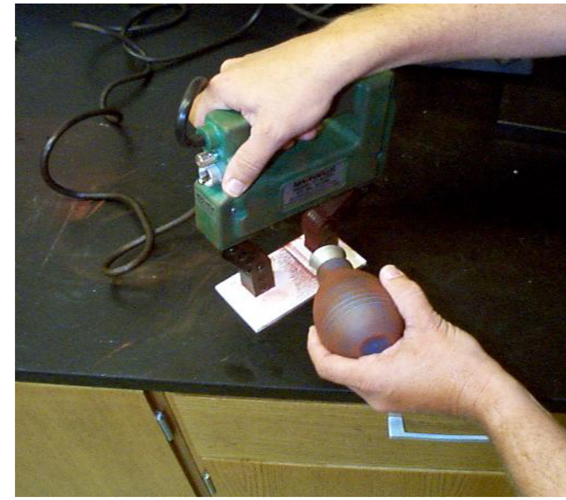






Application of Magnetic Media (Wet Versus Dry)

- MT can be performed using either dry particles or particles suspended in a liquid
- With the dry method, the particles are lightly dusted onto the inspection surface
- With the wet method, the part is flooded with a solution carrying the particles
- Dry method is more portable
- Wet method is generally more sensitive since the liquid carrier gives the magnetic particles additional mobility

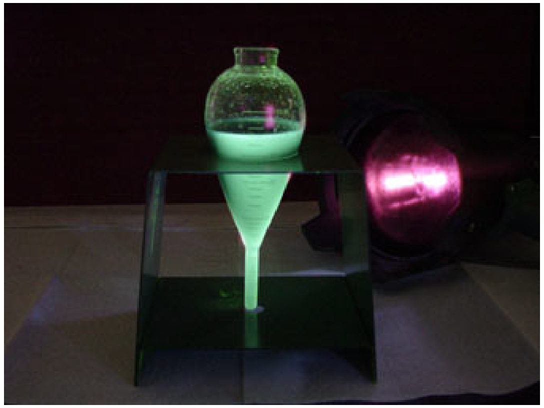


Dry Magnetic Particles

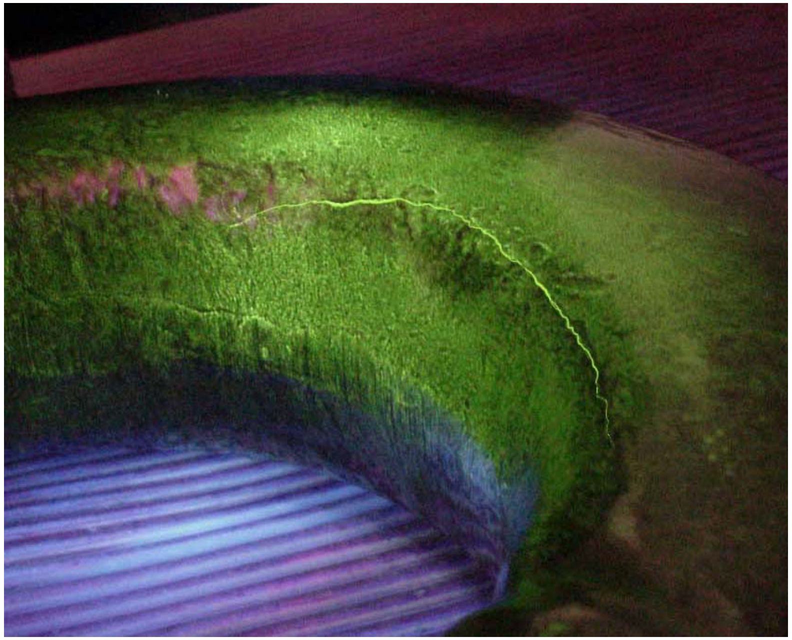
- Magnetic particles come in a variety of colors
- A color that produces a high level of contrast against the background should be used

Wet Magnetic Particles

- Wet particles are typically supplied as visible or fluorescent
- Visible particles are viewed under normal white light and fluorescent particles are viewed under black light

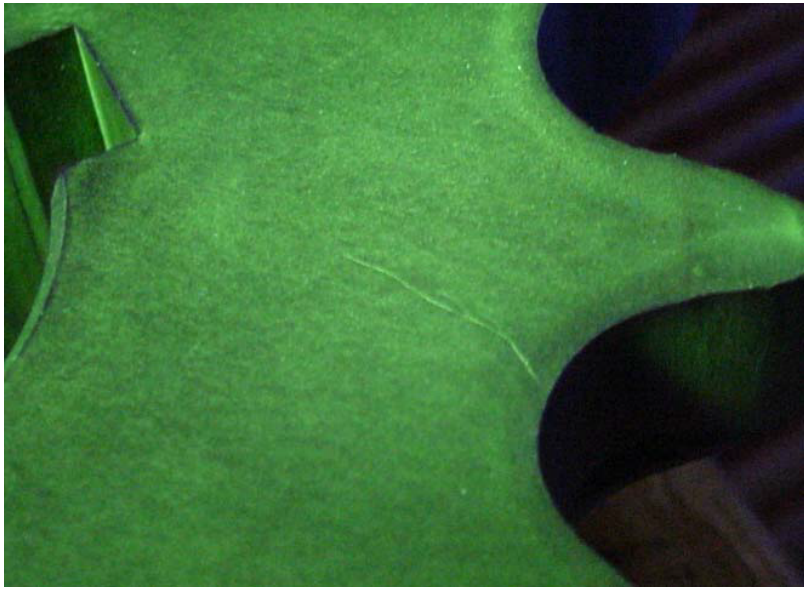


Crane Hook with Service Induced Crack



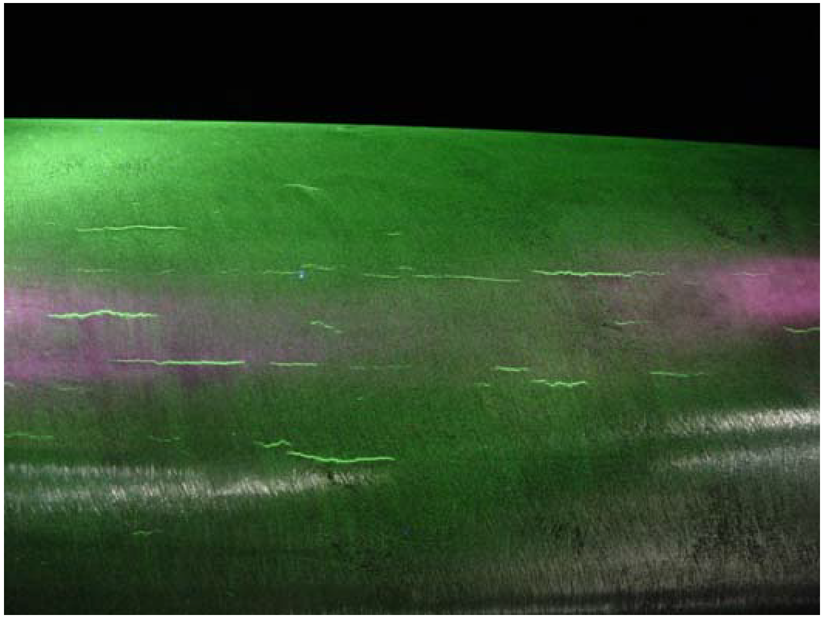
Wet Fluorescent Method

Gear with Service Induced Crack



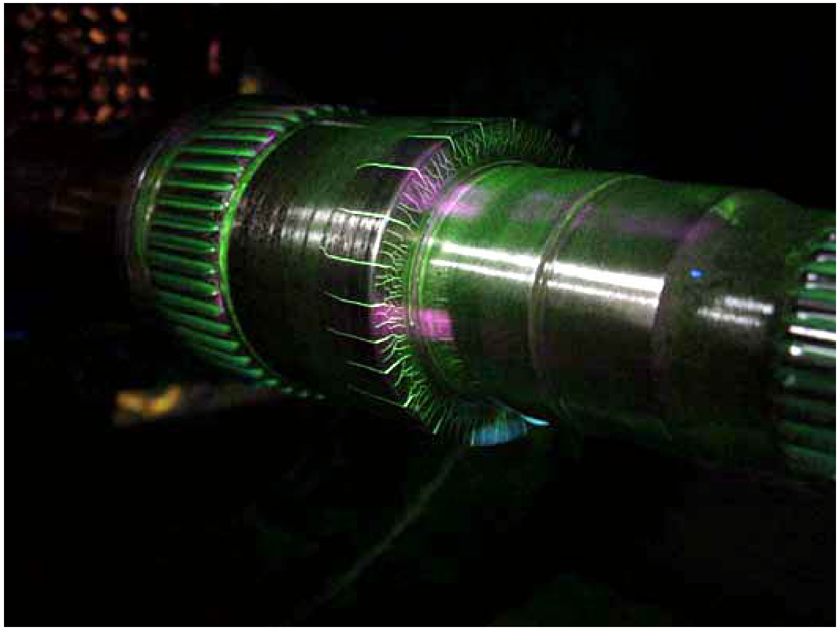
Wet Fluorescent Method

Drive Shaft with Heat Treatment Induced Crack



Wet Fluorescent Method

Splined Shaft with Service Induced Crack



Wet Fluorescent Method

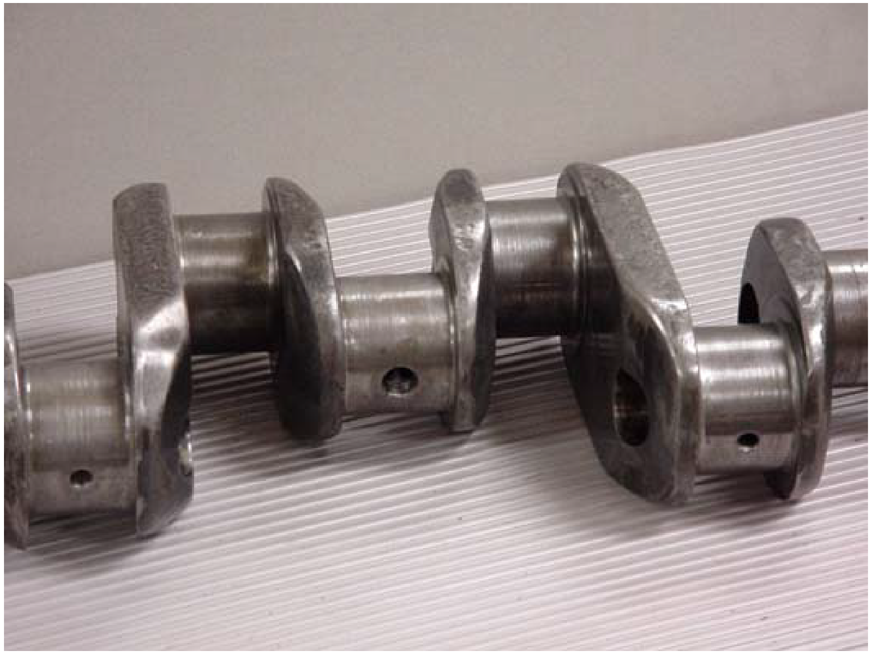
Threaded Shaft with Service Induced Crack

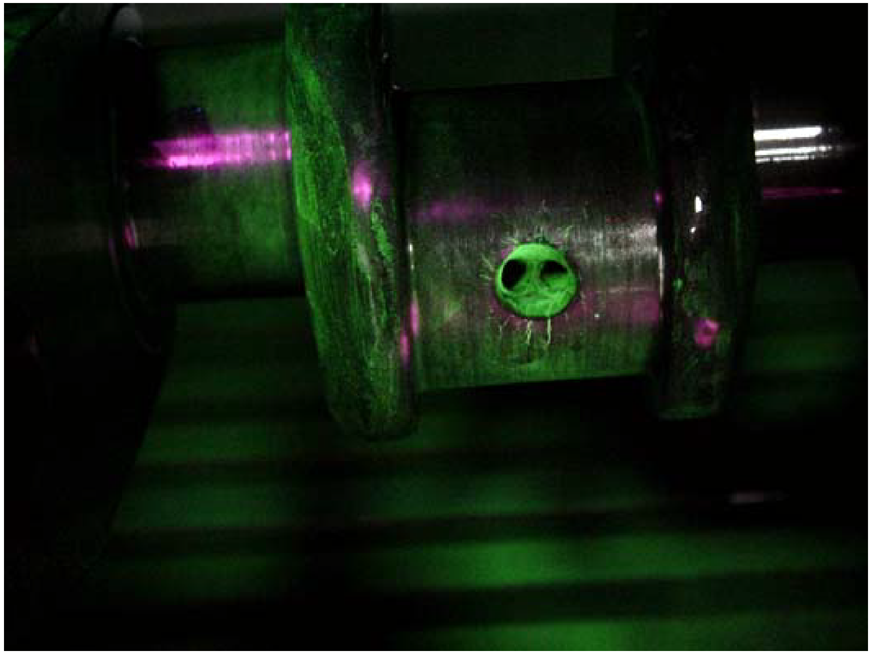
Wet Fluorescent Method

Large Bolt with Service Induced Crack

Wet Fluorescent Method

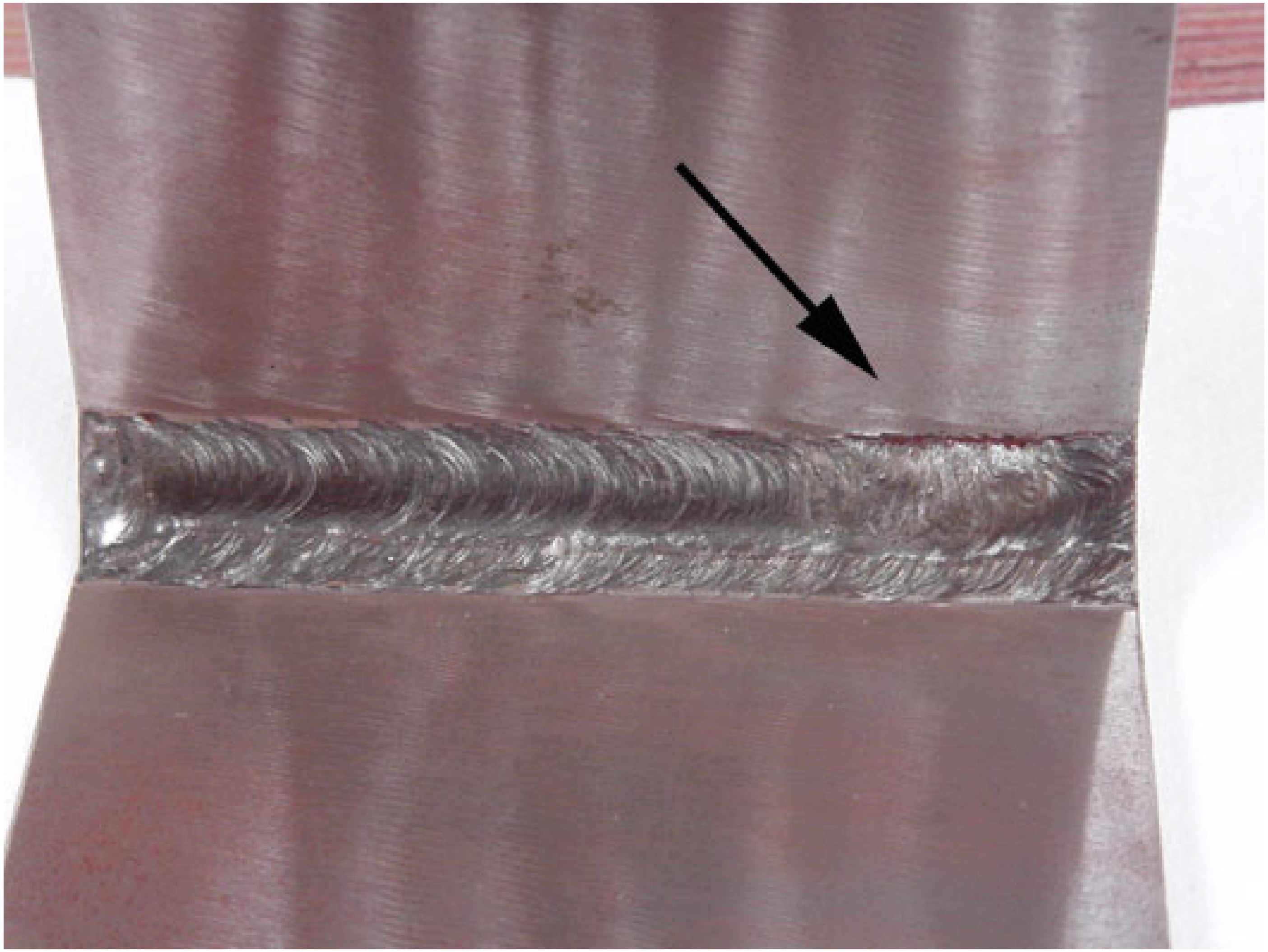
Crank Shaft with Service Induced Crack





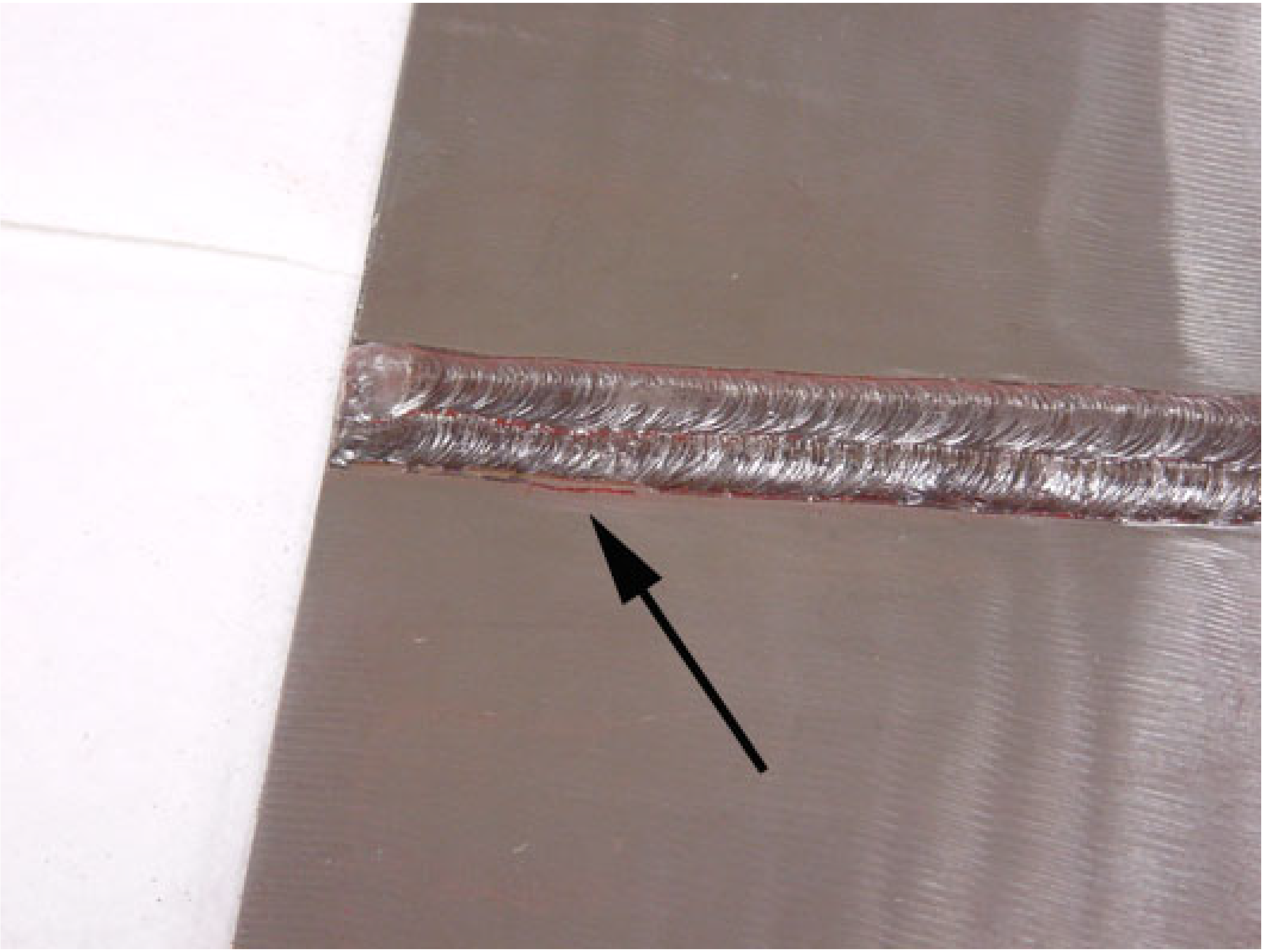
Wet Fluorescent Method

Lack of Fusion in SMAW Weld



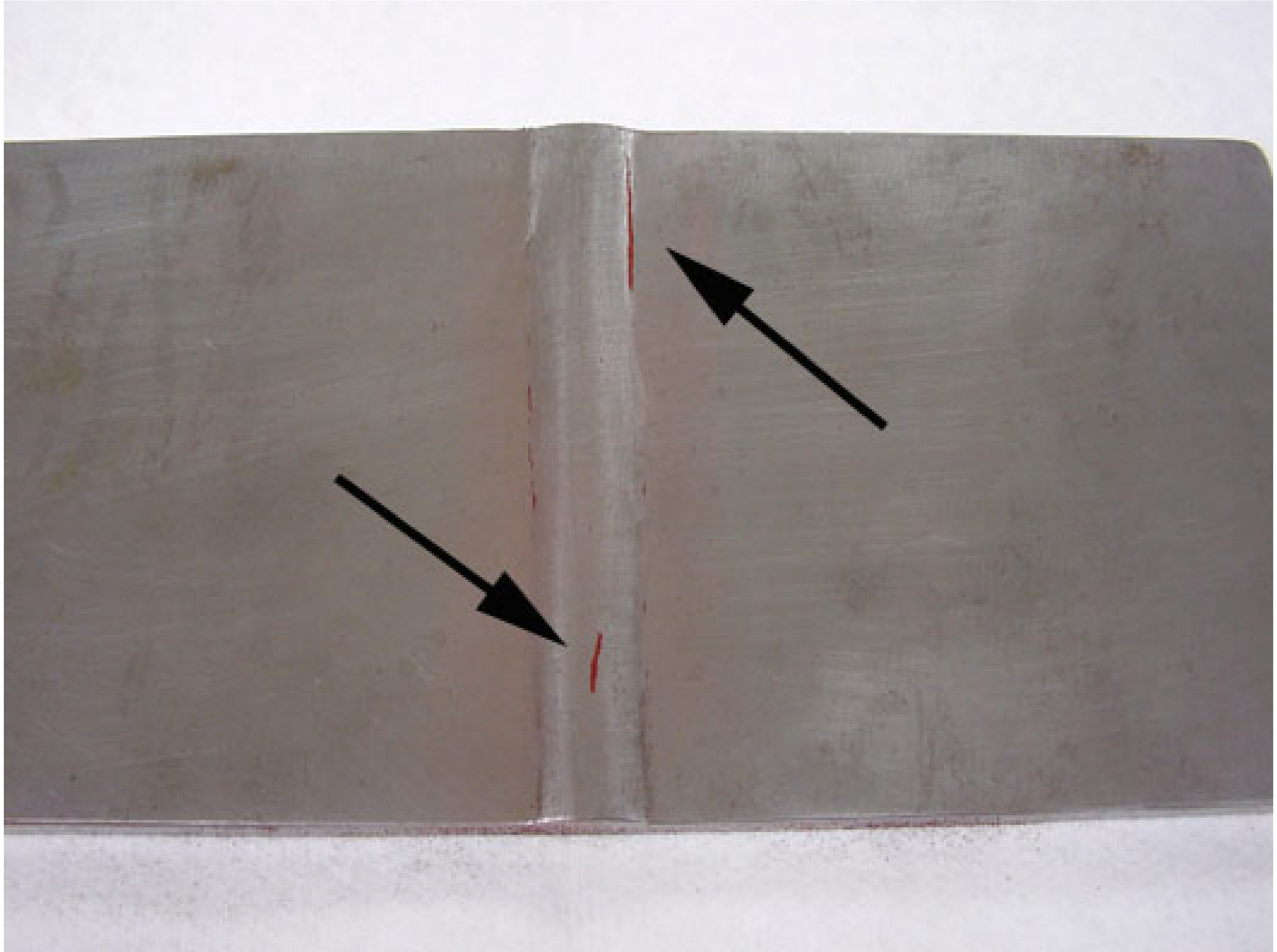
Visible, Dry Powder Method

Toe Crack in SMAW Weld



Visible, Dry Powder Method

Throat and Toe Cracks in Partially Ground Weld



Visible, Dry Powder Method

Demagnetization

- Parts inspected by the magnetic particle method may sometimes have an objectionable residual magnetic field that may interfere with subsequent manufacturing operations or service of the component
  - May interfere with welding and/or machining operation
  - Can effect gauges that are sensitive to magnetic fields if placed in close proximity
  - Abrasive particles may adhere to components surface and cause an increase in wear to engines components, gears, bearings etc.
- For these reasons demagnetization maybe required

ASME Section V Requirements

- ASME Section V, Article 7, Magnetic Particle Examination
  - T-720, General Requirements
    - Lists the requirements for written procedures and procedure qualifications
  - T-730, Equipment
    - Specifies the type of equipment needed as well as the particle type and temperature limitations
  - T-740, Miscellaneous Requirements
    - Include requirements for surface preparation and surface enhancement
  - T-750, Techniques
    - Describes different techniques used for magnetic particle testing
      - T-752, Prod Technique
      - T-753, Longitudinal Magnetization Technique
      - T-754, Circular Magnetization Technique
      - T-755, Yoke Technique
      - T-756, Multidirectional Magnetization Technique

ASME Section V Requirements

Requirement (as applicable)	Essential Variable	Nonessential Variable
Magnetizing technique	X	
Magnetizing current type or amperage outside range specified by this Article or as previously qualified	X	
Surface preparation	X	
Magnetic particles (fluorescent/visible, color, particle size, wet/dry)	X	
Method of particle application	X	
Method of excess particle removal	X	
Minimum light intensity	X	
Existing coatings, greater than the thickness demonstrated	X	
Nonmagnetic surface contrast enhancement, when utilized	X	
Performance demonstration, when required	X	

ASME Section V Requirements

Requirement (as applicable)	Essential Variable	Nonessential Variable
Examination part surface temperature outside of the temperature range recommended by the manufacturer of the particles or as previously qualified	X	
Shape or size of the examination object		X
Equipment of the same type		X
Temperature (within those specified by manufacturer or as previously qualified)		X
Demagnetizing technique		X
Post-examination cleaning technique		X
Personnel qualification requirements		X

ASME Section V Requirements

- ASME Section V, Article 7, Magnetic Particle Examination
  - T-760, Calibration
    - Covers the calibration requirements of the testing equipment which includes checking magnetic field strength and orientation
  - T-770, Examination
    - Lists the examination steps
      - T-772, Direction of Magnetization
        - Specifes that the area to be tested shall be tested twice with the magnetic field of the second inspection perpendicular to the magnetic field of the first inspection
        - T-773, Method of Examination
        - T-774, Examination Coverage
        - T-775, Rectified Current
        - T-776, Excess Particle Removal
        - T-777, Interpretation
        - T-778, Demagnitization
        - T-779 Post-Examination Cleaning

ASME Section V Requirements

- ASME Section V, Article 7, Magnetic Particle Examination
  - T-780, Evaluation
    - Covers the evaluation requirements and references the code of construction
      - ASME Section III or ASME B31.1
  - T-690, Documentation
    - Defines what are considered rejectable and non-rejectable indications and describes the minimum requirements for the examination record
      - Procedure used
      - Magnetic particle equipment and current used
      - Examination personnel
      - Map or record of indications
      - Material and thickness
      - Date of examination

ASME Section III – NB and B31.1 Acceptance Requirements for Magnetic Particle Testing

- Section NB-5340 of ASME Section III provides magnetic particle examination acceptance criteria
- Section 136.4.3 of ASME B31.1 provides magnetic particle examination acceptance criteria
- Both standards references ASME Section V, Article 7

Criteria	ASME Section III – NB	ASME B31.1
Crack or Linear Indication	Unacceptable	
Rounded Indications	Any single indication greater than 3/16 in.	
	Four or more indications in a line separated by 1/16 in or less edge to edge	
	Ten or more indications in any 6 in^2 of surface	

Advantages of Magnetic Particle Inspection

- Can detect both surface and **VERY NEAR** sub-surface defects
- Can inspect parts with irregular shapes easily
- Pre-cleaning of components is not as critical as it is for some other inspection methods. Most contaminants within a flaw will not hinder flaw detectability
- Fast method of inspection and indications are visible directly on the specimen surface
- Considered low cost compared to many other NDT methods
- Is a very portable inspection method especially when used with battery powered equipment

Limitations of Magnetic Particle Inspection

- Cannot inspect non-ferrous materials such as aluminum, magnesium or most stainless steels
- Inspection of large parts may require use of equipment with special power requirements
- Some parts may require removal of coating or plating to achieve desired inspection sensitivity
- Limited subsurface discontinuity detection capabilities. Maximum depth sensitivity is approximately 0.6” (under ideal conditions)
- Post cleaning, and post demagnetization is often necessary
- Alignment between magnetic flux and defect is important

Eddy Current Testing

Module 6A.4

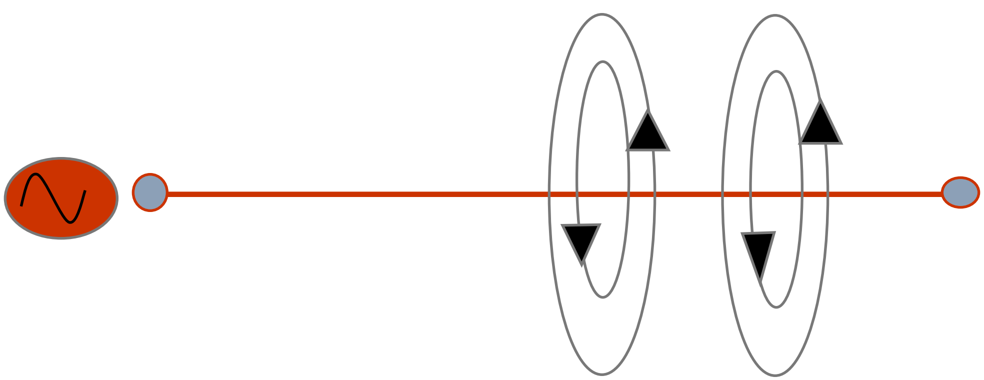
History

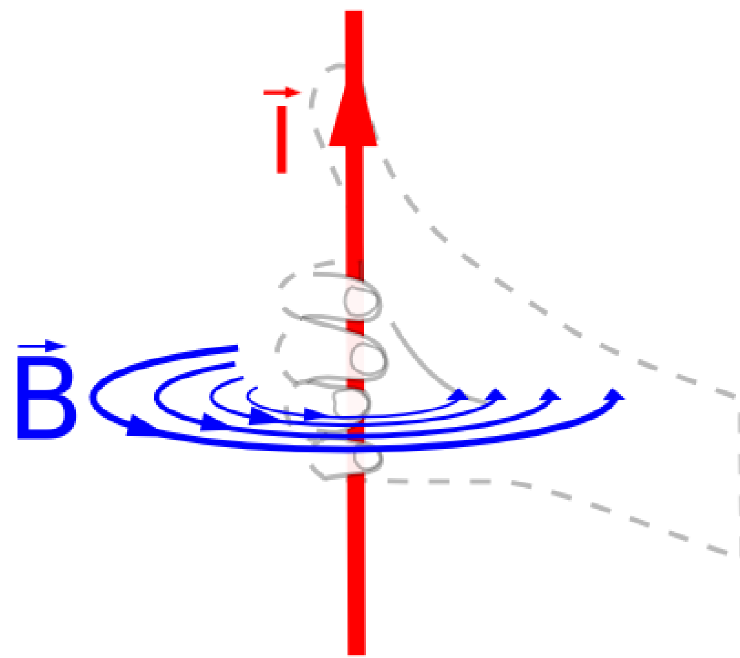
- 1879 - D. Hughes sorting of genuine and counterfeit coins
- 1881 - A. Bell induction sensing device for bullet in President J. Garfield (missed)
- 1933 - Kaiser-Wilhelm-Institute developed industrial system
- 1948 - Förster founded his own company in Reutlingen
- 1950 - F. Förster theory and instrumentation
- 1960 - proliferation of testing equipment

Moore, P., *Nondestructive Testing Handbook,* third edition: Volume 5, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 2004

Electromagnetic Induction

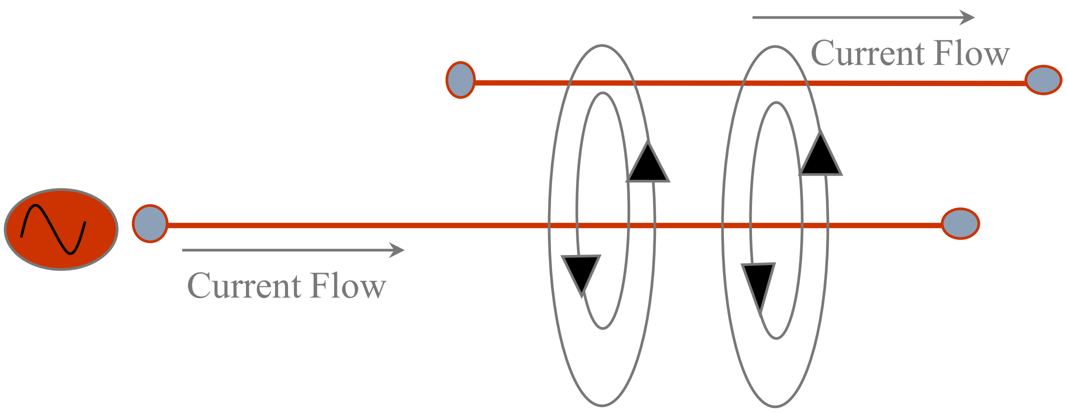
- Eddy currents are created through a process called electromagnetic induction
- When alternating current is applied to the conductor, such as copper wire, a magnetic field develops in and around the conductor
- This magnetic field expands as the alternating current rises to maximum and collapses as the current is reduced to zero





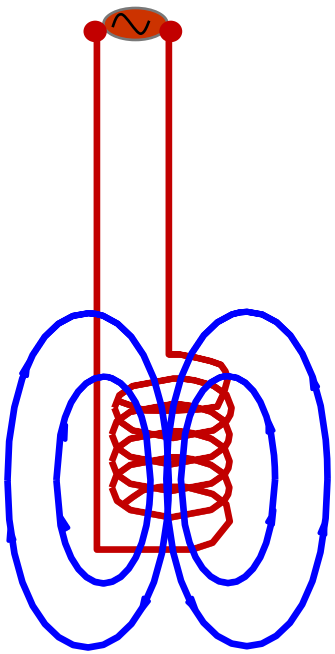
Electromagnetic Induction

- If another electrical conductor is brought into the proximity of this changing magnetic field, the reverse effect will occur
- Magnetic field cutting through the second conductor will cause an “induced” current to flow in this second conductor
- Eddy currents are a form of induced currents



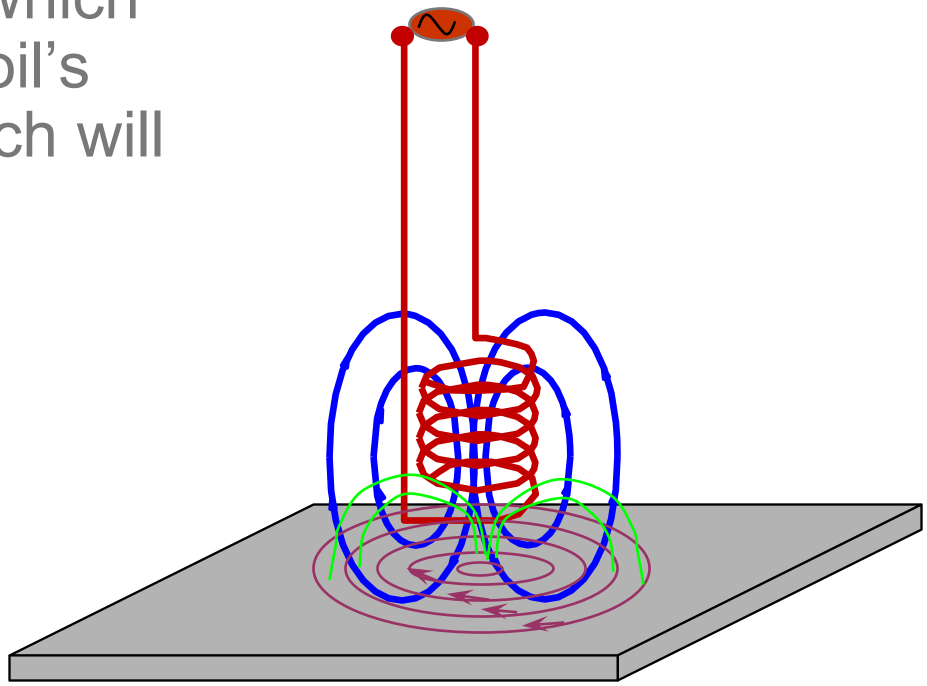
Generation of Eddy Currents

- In order to generate eddy currents for an inspection a “probe” is used
- Inside the probe is an electrical conductor which is formed into a coil
- Alternating current is allowed to flow in the coil at a frequency chosen by the technician for the type of test involved
- A dynamic expanding and collapsing magnetic field forms in and around the coil as the alternating current flows through the coil



Generation of Eddy Currents

- When an electrically conductive material is placed in the coil's dynamic magnetic field electromagnetic, induction will occur and eddy currents will be induced in the material
- Eddy currents flowing in the material will generate their own "secondary" magnetic field which will oppose the change of coil's "primary" magnetic field which will change the coil impedance



Electricity – Alternating Current

- Impedance
  - Capability of AC element or circuit to conduct AC current
- Vectorial representation
  - Vectors (usually space related) or rather phasors (time related vectors) are used to represent currents, voltages and impedances in AC circuits

$$|\dot{Z}| = \sqrt{R^2 + X_L^2}$$

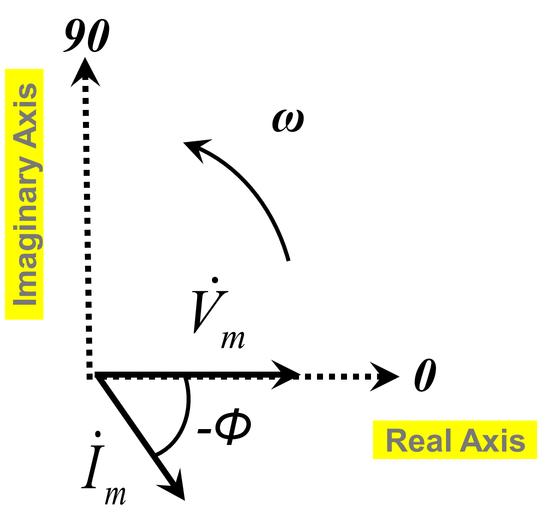
Impedance Modulus

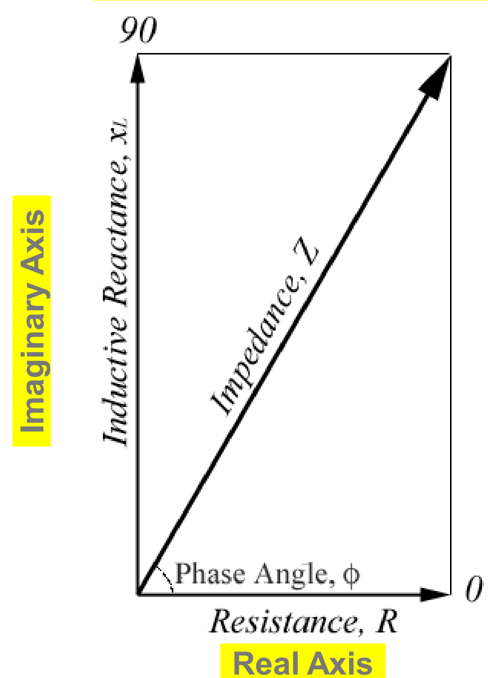
$$X_L = \omega L$$

Inductive Reactance

$$\tan\phi = \frac{X_L}{R}$$

Phase Angle Calculated from Vectorial Presentation

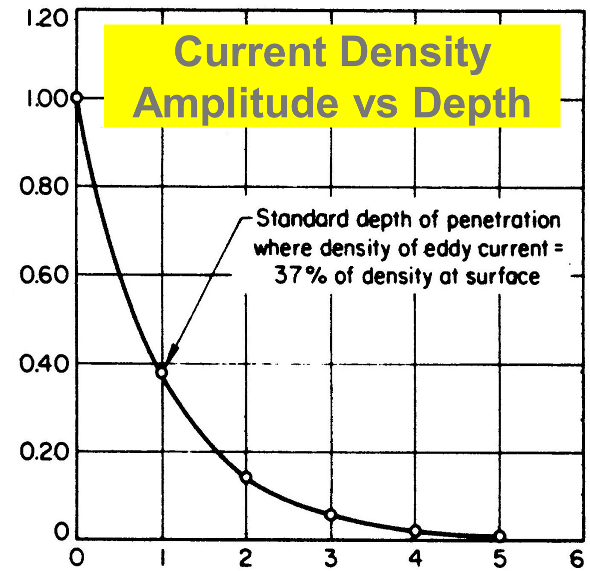


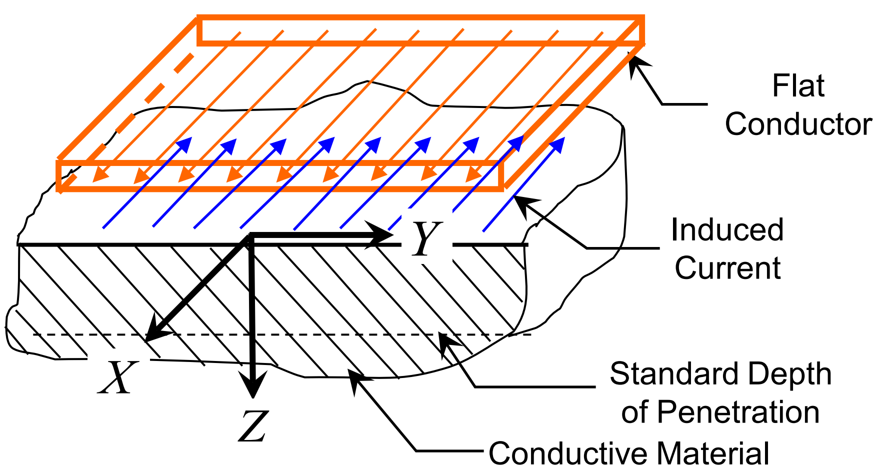


Moore, P., *Nondestructive Testing Handbook,* third edition: Volume 5, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 2004

Theory of EC – Depth of Penetration

- Variation of amplitude and phase of current
  - Amplitude attenuates exponentially and phase changes linearly with depth in material
- Depth of standard penetration depends on material properties and frequency
- Defect signal with increasing depth
  - Signal from identical defects at different depths will decrease
  - Signal phase angle from defect will increase





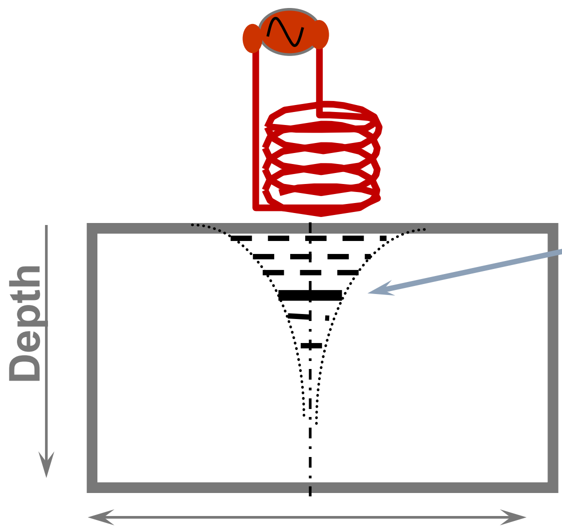
$$\delta = \sqrt{\frac{2}{\omega\sigma\mu_0\mu_r}}$$

Standard Depth of Penetration for Magnetic Material.

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu_0}}$$

Standard Depth of Penetration for Nonmagnetic Material

Depth of Penetration Illustration



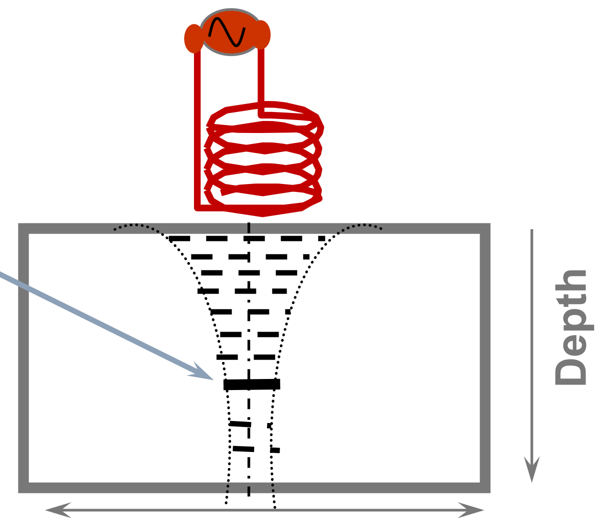
Eddy Current Density

High Frequency
High Conductivity
High Permeability

Shallow

Standard Depth of Penetration (Skin Depth)

1/e or 37 % of surface density



Eddy Current Density

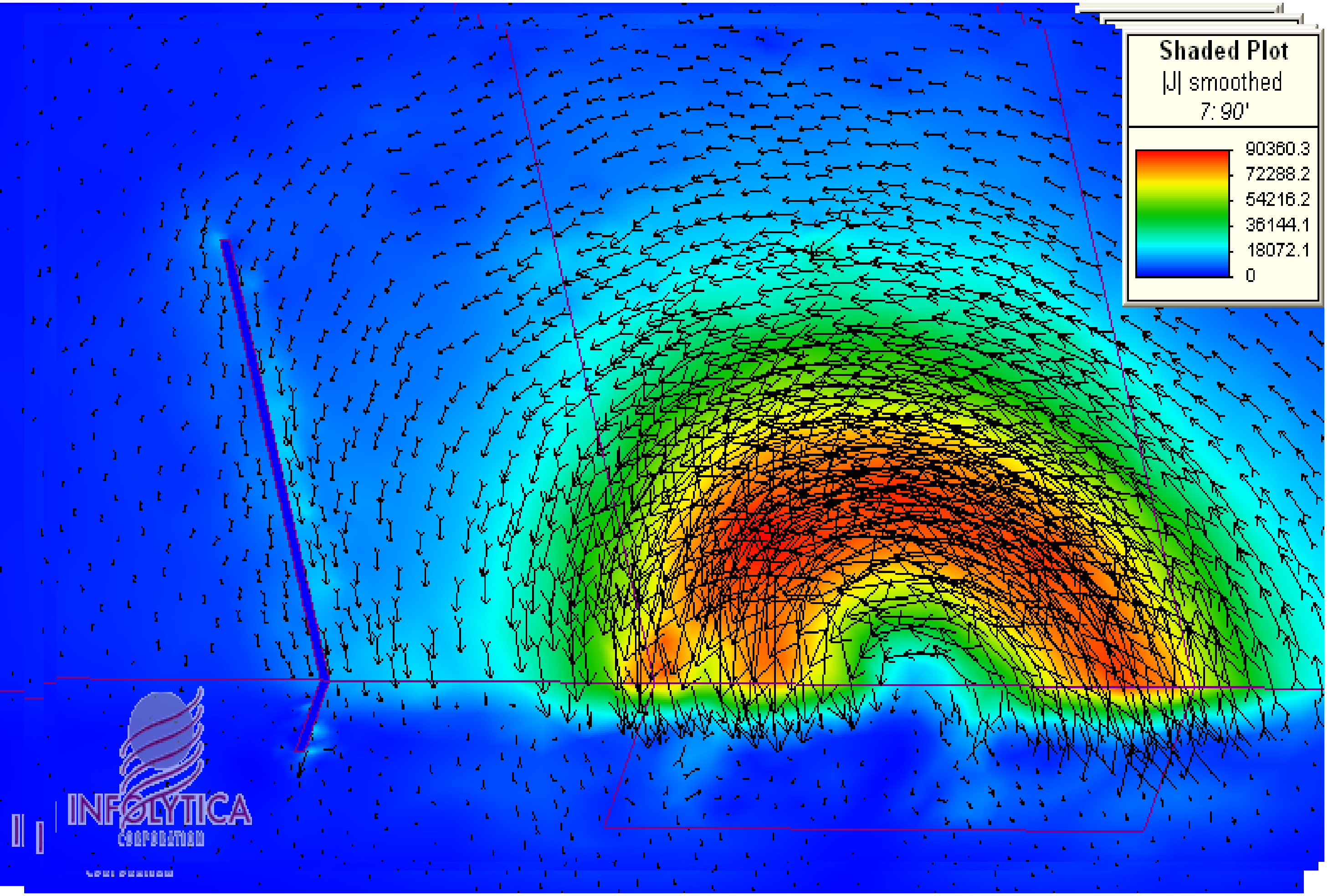
Low Frequency
Low Conductivity
Low Permeability

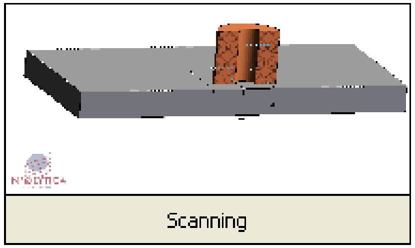
Deep

Geometric Flaw Characterization – Current Interruption

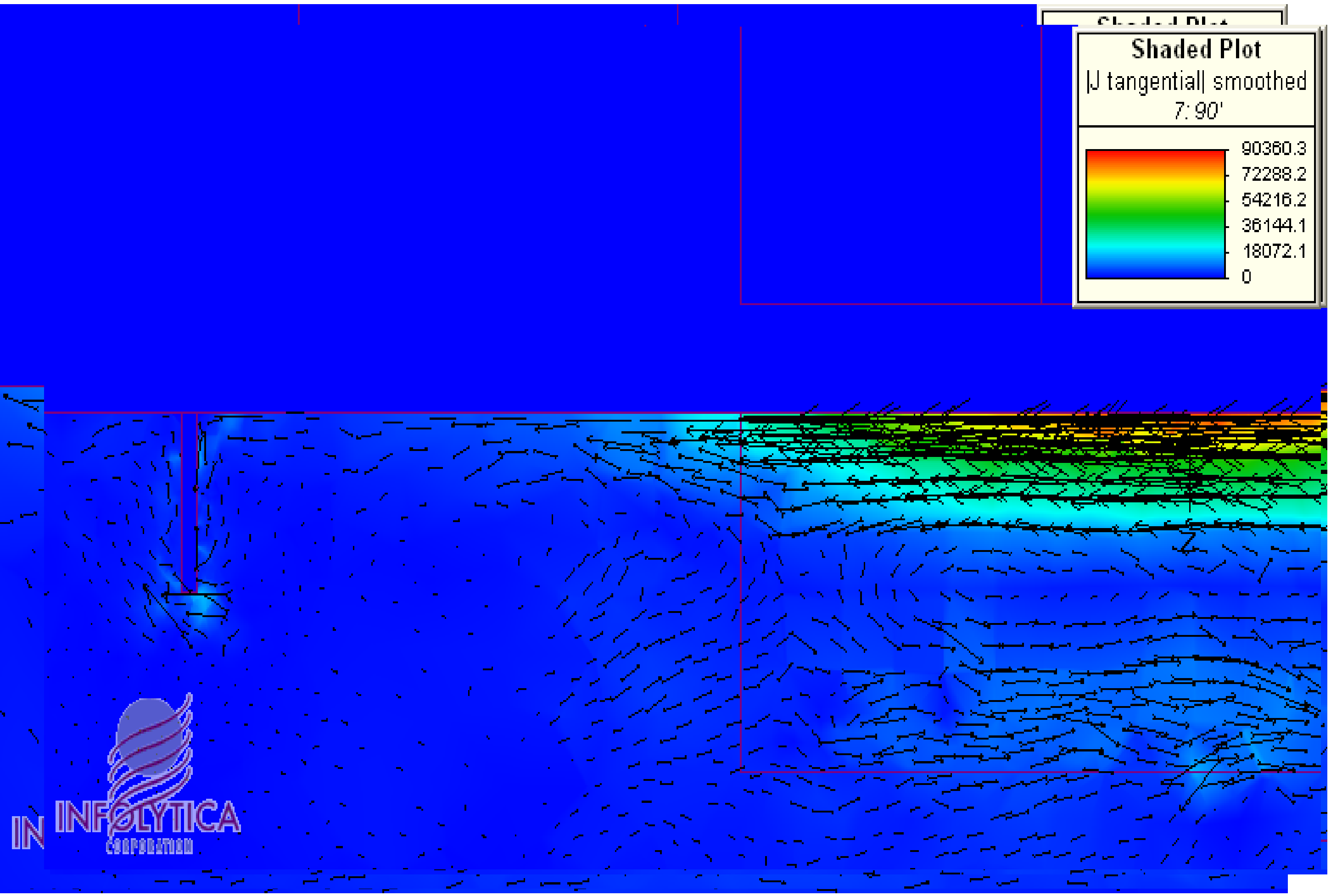
- Hypothesis of interrupted currents
  - Increased resistance
  - Changed inductance
- Case of point defects
  - Point defect will cause small interruption of eddy current contours if point defect size is relatively small compared to size of coil
- Case of large defects
  - Larger defects will cause large interruption of eddy current contours and will easily be detected
  - Interruption will also depend on defect orientation. If defect is parallel (delaminations) to EC contours it may be missed even if large
- Case of multiple defects
  - Multiple defects will be easy to detect but may be difficult to separate

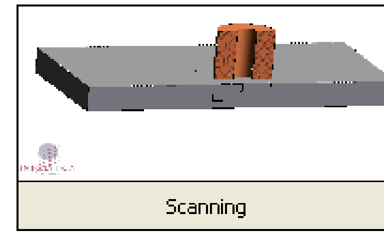
ET Interaction with Flaw – Current Interruption (3D View)





ET Interaction with Flaw – Current Interruption (2D View)





Probes – Principles and Basic Characteristics

- Induction and reception functions
  - Parametric
  - Transformer
- Absolute and differential measure
  - Absolute
  - Differential
- Types of probes – parametric and transformer, absolute and differential, surface and encircling or internal, any combination of above.

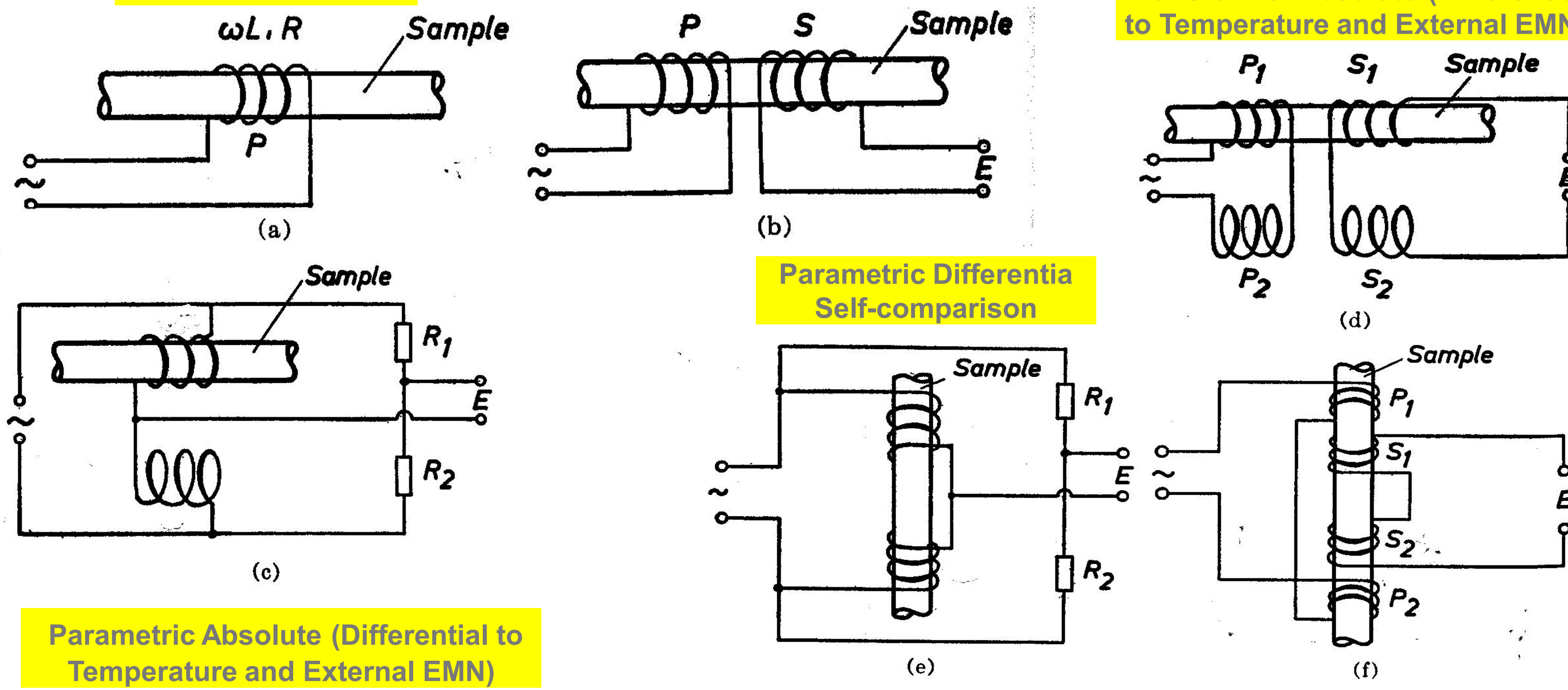
Probe Arrangements for Long Bars

Parametric Absolute

Transformer Absolute

Transformer Absolute (Differential to Temperature and External EMN)

Parametric Differentia Self-comparison



Parametric Absolute (Differential to Temperature and External EMN)

Transformer Differential Self-comparison

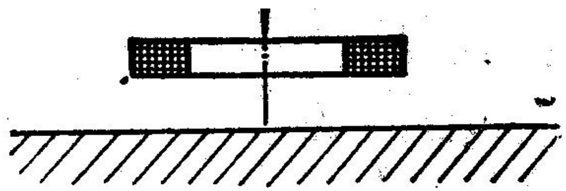
P – Primary Or Transmitter
S – Secondary Or Receiver

MOVIE
Encircling

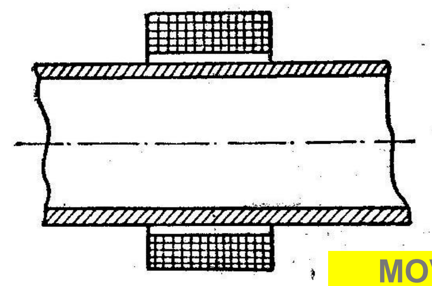
McMaster, R., *Nondestructive Testing Handbook*: Volume 2, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 1959

Probe Arrangements for Plates, Sheets and Tubes

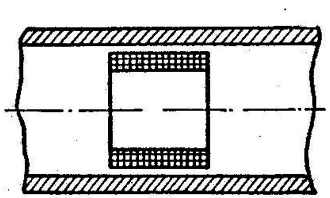
Surface Parametric Absolute



Encircling Parametric Absolute

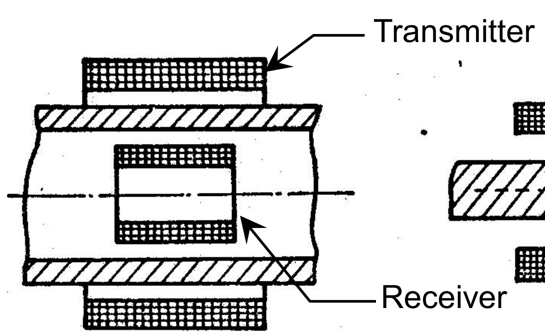


Internal Parametric Absolute

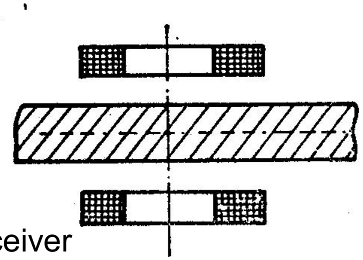


MOVIE
BobbinProbe

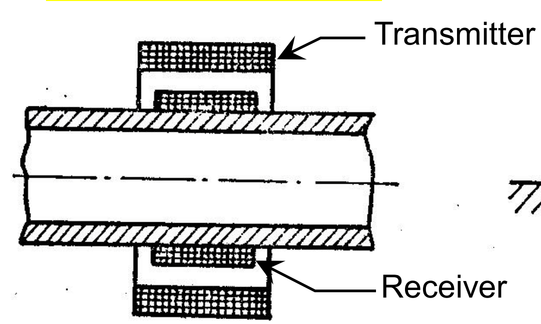
Screen Transformer Absolute (Transmitter/ Receiver)



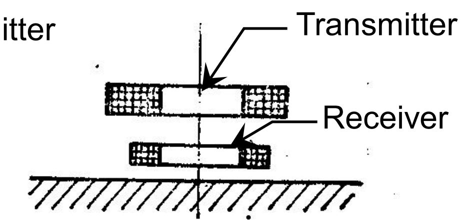
Screen Surface Parametric-differential or Transformer-Absolute



Encircling Transformer Absolute

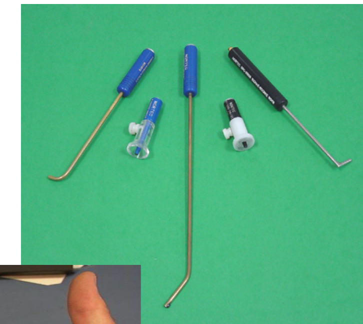
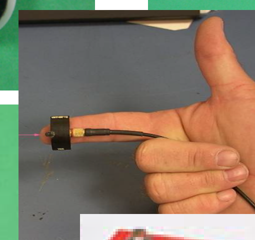


Surface Transformer Absolute

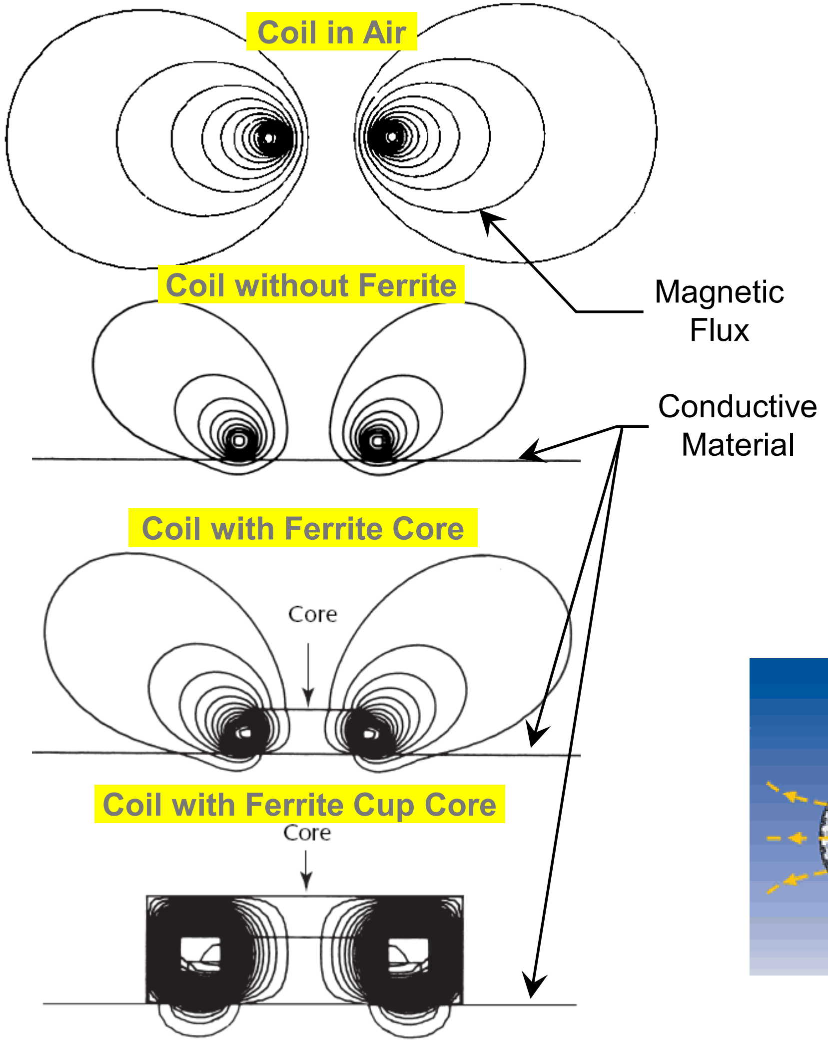


Different Probe Designs and Applications

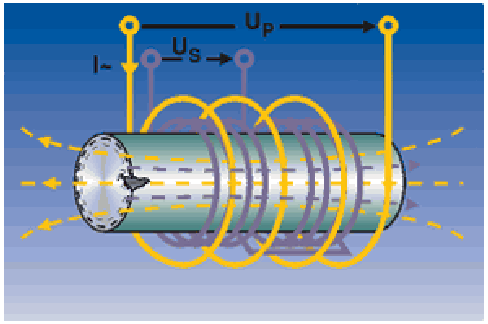
- Surface spot probes
- Pencil probes
- Sliding and ring probes
- Bolt hole probes
- Encircling probes
- Internal or bobbin probes

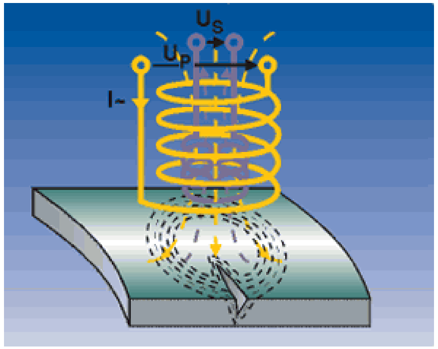





Probes – EC Distributed Related to Coil Position



- Field generated by non-load inductor coil
- EC contours in the part related to juxtaposition between the coil and the part
- Distance/Lift off effect on coupling in various probes
- Focusing means





Moore, P., *Nondestructive Testing Handbook,* third edition: Volume 5, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 2004

Probes – Reaction of Different Coils According to Coil Shape

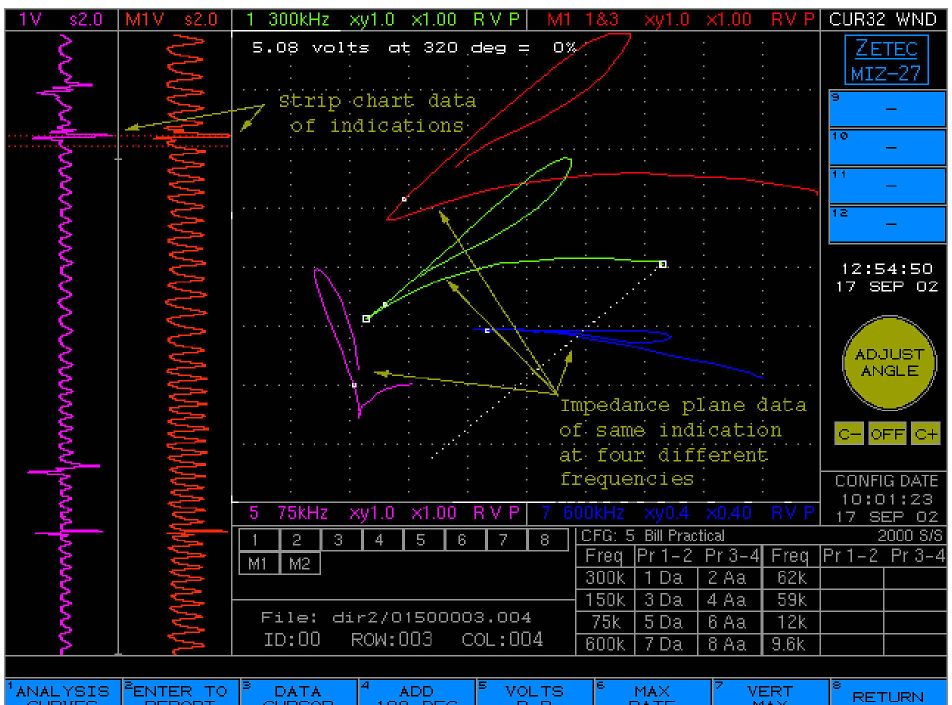
- Reaction to small flaws
  - Reaction strongly depends on the ratio of flaw-to-probe size
    - The higher the ratio the better the sensitivity to flaw but worse the sensitivity to lift off
  - Differential probes with self-comparison are better for detection of small flaws than absolute
- Reaction to long flaws
  - Long flaws are those that are longer than the diameter of surface or pencil probes or longer than the width of encircling/internal probes
  - Differential probes will only indicate the begging and the end of long flaws whereas the absolute will indicate the entire length of long flaws
- Reaction to continuous (e.g. seam weld) flaws
  - Absolute or self-comparison differential probes may not be adequate for this application
  - May require differential arrangement with separate reference specimen

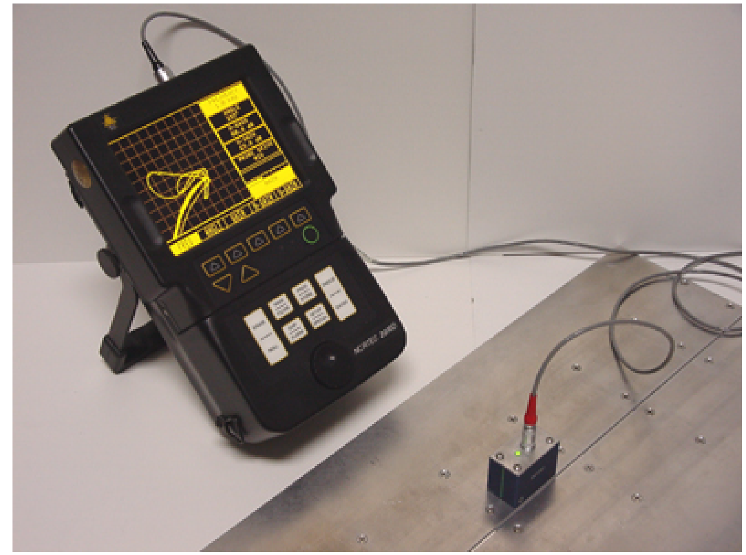
Probes – Technology and Practical Characterization

- Critical design factors
- Manufacturing/design technology
- Electric parameters
- Maintenance
- Many factors possible to simulate through modeling

Equipment – Different Types of EC Equipment

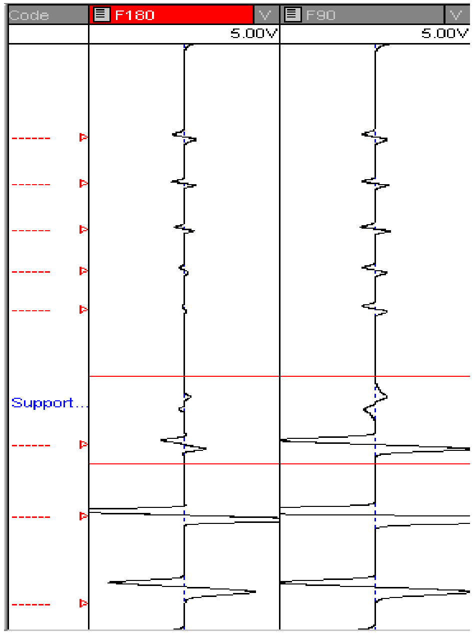
- Mono-parameter, mono-channel and specialized
- Multi-parameter and multi-channel
- Advantages of multi-parameter





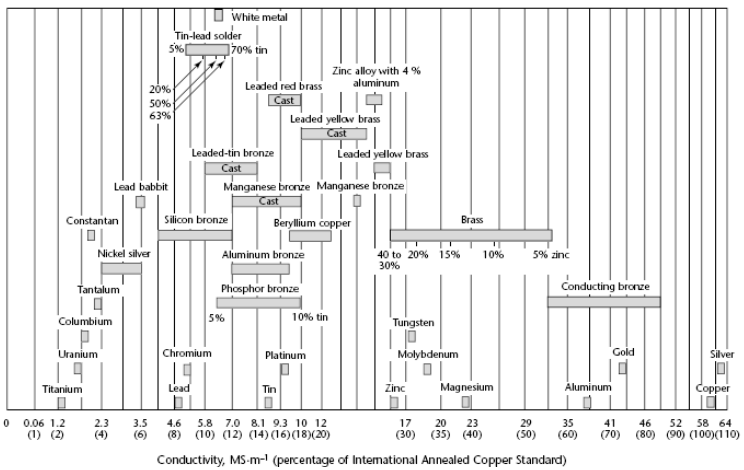
Equipment – Auxiliary Devices

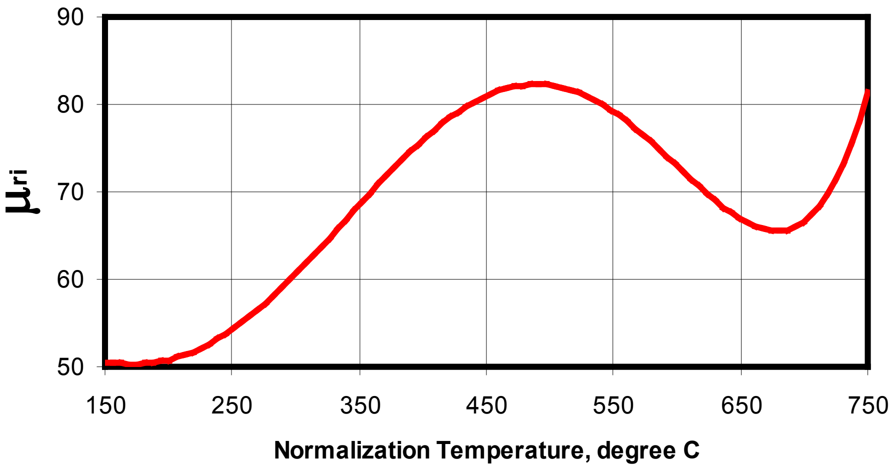
- Auxiliary devices for signal acquisition
- Driving mechanism, Saturating unit, Demagnetizer
- Equipment of signal storage
- System for automatic processing of signals



Materials and Products – Electromagnetic Properties

- Electric conductivity
  - Chemical
  - Temperature
  - Grain size
  - Texture
  - Structure
- Magnetic permeability
  - Chemical analysis
  - Temperature
  - Grain size
  - Texture
  - Structure





Moore, P., *Nondestructive Testing Handbook,* third edition: Volume 5, *Electromagnetic Testing*, Columbus, OH, American Society for Nondestructive Testing, 2004

Materials and Products – Main Discontinuities Detected by EC

- Production – surface and slightly subsurface
  - Solidification cracks
  - Pores
  - Chemical and phase composition
  - Welding
- Processing (hot or cold)
  - Discontinuities
  - Heat treatment
  - Residual stresses and hardness
  - Phase composition
- In-services
  - Creep
  - Fatigue
  - Corrosion

Influence of Parameters – Flaw Position and Orientation

- EC contours
  - Contours must be as close to perpendicular to the flaw plane as possible to generate max response
- Penetration depth
  - Best detection and sizing possible in one to two standard depth of penetrations
- Zone of probe action
  - Non-shielded - Extends several depths of penetration around probe tip on inspected surface
  - Shielded – Area around the probe is significantly reduced due to focusing ferrite and soft magnetic iron means

Influence of Parameters – Material Temperature

- Heating – Temperature affects material properties
  - Resistivity increases with the temperature increase
  - Magnetic properties are lost above Curie temperature
  - Local areas of spontaneous magnetization may appear on surface of hot rolled materials due to local cooling
- Compensation
  - Differential and particularly transformer differential probes are best temperature compensated
  - Probes may need cooling or must be cooled when testing materials after the furnace or hot rolling processing

Influence of Parameters – Geometry and Structure of Part

- Choice of test frequency
  - Very important to optimize the operating point on the impedance plane diagram for best separation and sensitivity
- Phase discrimination
  - Flaw depth measurements is better done with phase measurements in many cases
  - Frequency selection important for better signal separation/discrimination by phase
- Filtering
  - Reduces noise from fluctuating properties, vibration, electrical sources etc
- Magnetic saturation
  - Used mainly for inspection of thin wall magnetic tubes as nonmagnetic (improved penetration) during saturation

Influence of Parameters – Coupling

- Vibration
  - Must be eliminated through mechanical means or filtered electronically
- Centering
  - For encircling, internal tube and bolt hole probes, ensures the sensitivity is uniform along the tube or hole circumference
- Sensitivity
  - Sensitivity is reduced when the coupling (usually increased distance) is reduced
- Compensation
  - Use means for centering and stabilization of probe movement as close to inspected surface as possible
  - Design probes less sensitive to coupling variations

Influence of Parameters – Speed Relative Part vs. Probe

- Defect spatial frequency (f_{defect})
- Examples of defect frequency at different inspection speeds
  - Defect frequency of 100 Hz is obtained at testing speed of 0.3 m/s (1 ft/s) with probe diameter of 3 mm
  - Defect frequency of 1 kHz is obtained at testing speed of 3 m/s (10 ft/s) with probe diameter of 3 mm

$$f_{defect} = \frac{V_{test}}{D_{coil}}$$

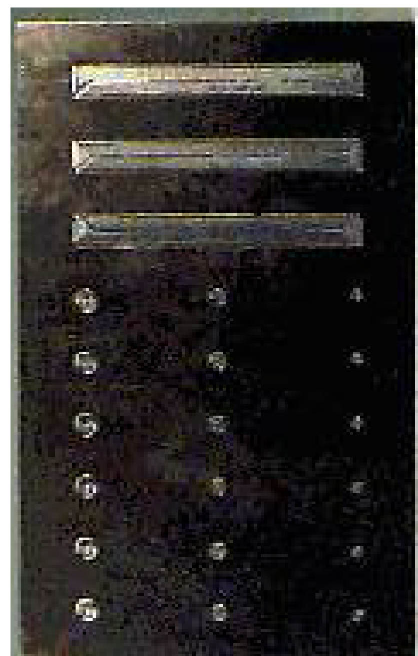
- Bandwith of equipment according to testing speed
  - Bandwith is increased with increased inspection speed
  - Further bandwidth increase is required when several probes are simultaneously used in multiplex arrangement
  - Important to select adequate equipment for the expected inspection speeds
  - Filter settings must be adjusted correctly for automated inspection applications

Inspection Procedures – Reference Standards

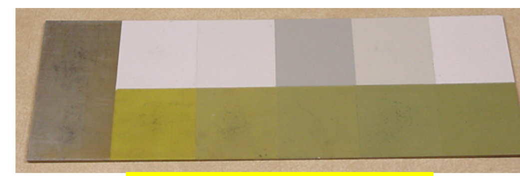
- Reference standards are used to assure repeatability and provide acceptance criteria
  - Choice of reference standards is very important
- Various types of reference standards including fabrication, reproducibility types
  - EDM notches
  - Actual flaws
  - Drilled holes or machined grooves

Tube Standards

EDM Notches (Crack Simulation)



Corrosion Standard



Coating Standard

Multipurpose - EDM Notches and Conductivity

MOVIE
TubCalibrSpec

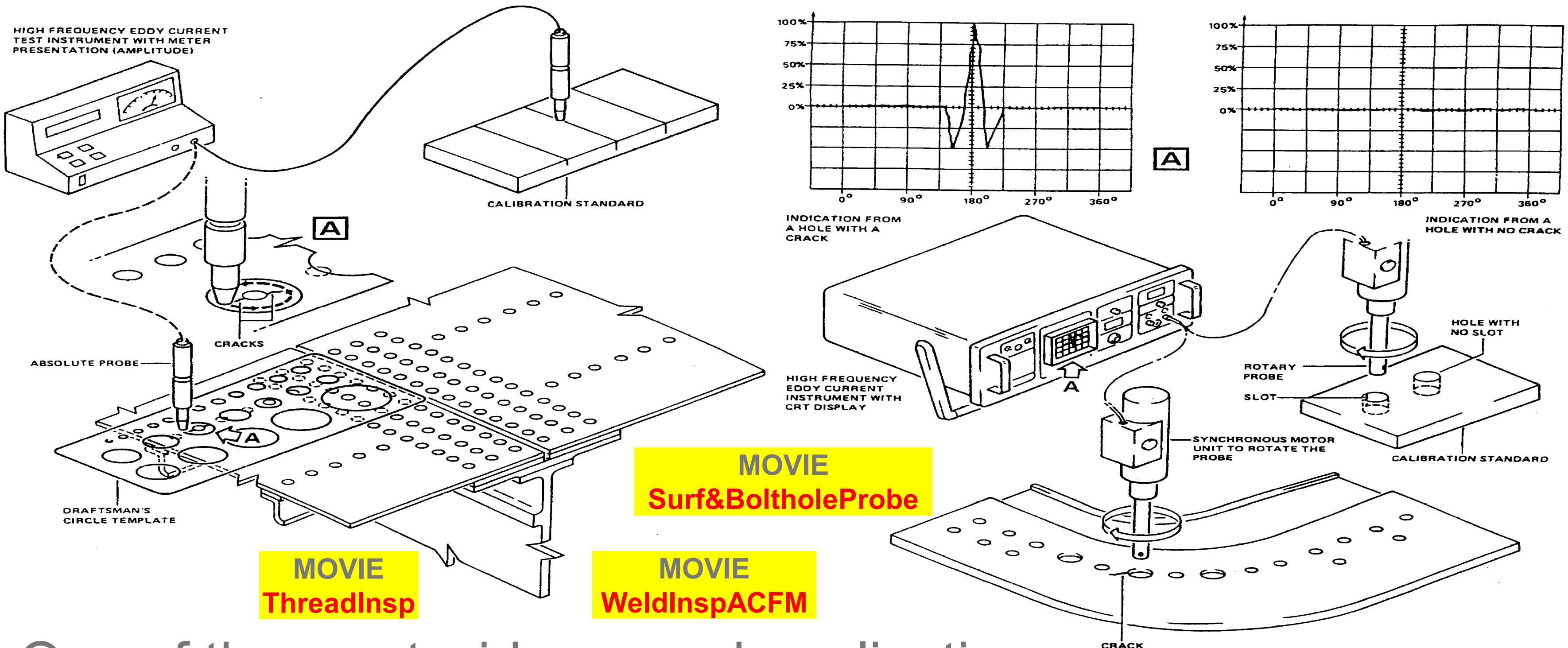
Inspection Procedures – Inspection

- Access
- Surface preparation
- Speed
- Use of auxiliary devices
- Inspection range
- Indication recording

Main Applications of EC Testing – Flaw Detection

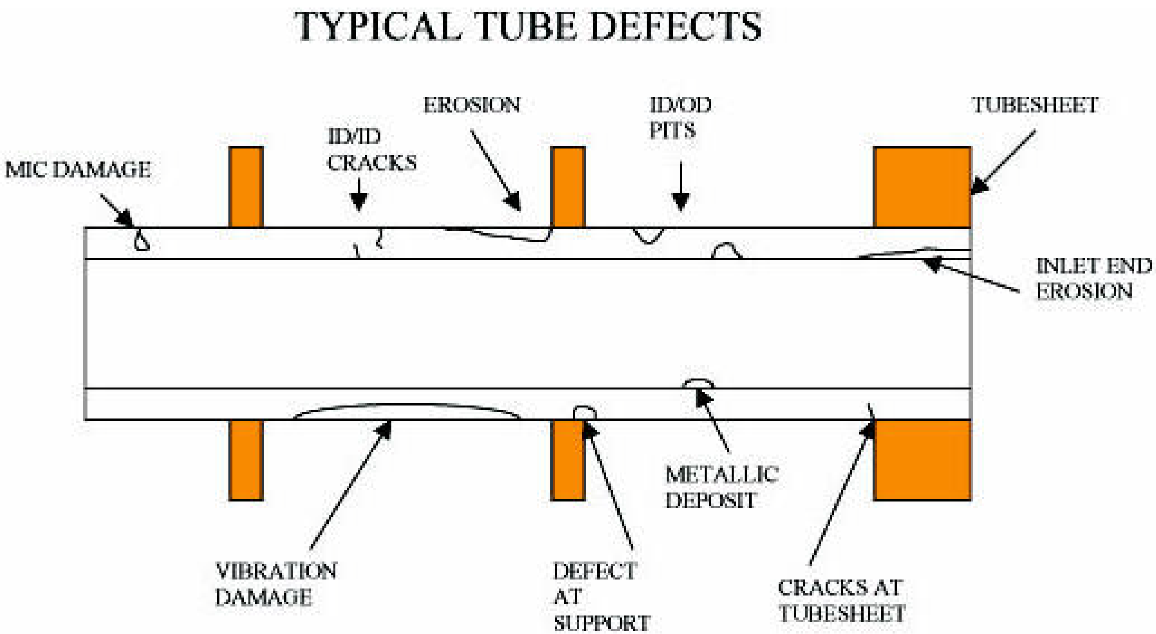
- Absolute measurements
  - Inspection for properties that change gradually (see slides with probe types)
- Differential measurements
  - Detection of relatively small and localized discontinuities (see slides with probe types)

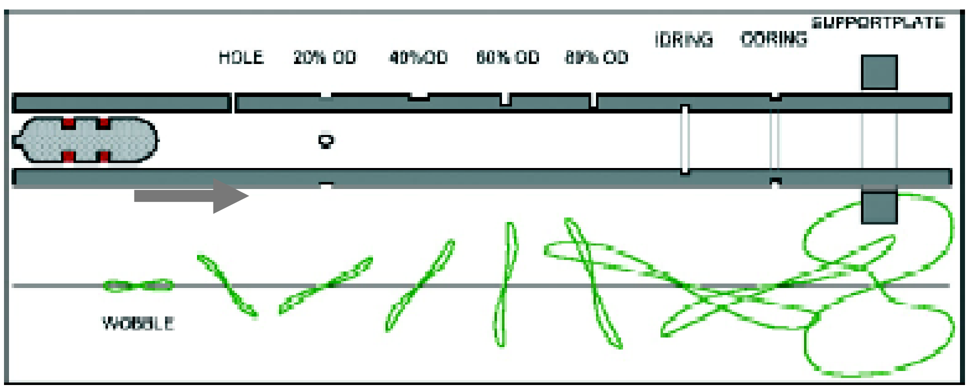
Main Applications of EC Testing – Surface Flaw Detection

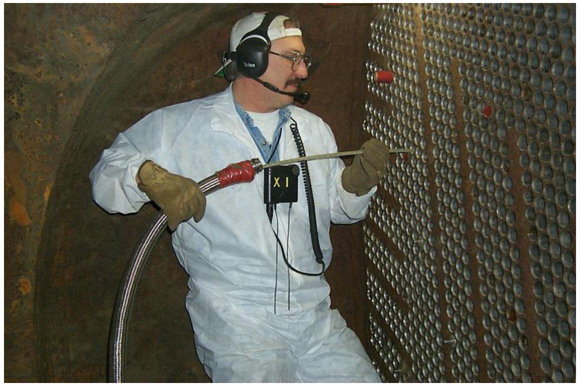


- One of the most wide-spread applications
- Conducted manually, semi- or fully-automated
- In many cases, superior to other surface inspection methods (LPI, MPI, UT)
- Performed through paint, coatings or at a distance from surface

Main Applications of EC Testing – Tube Flaw Detection





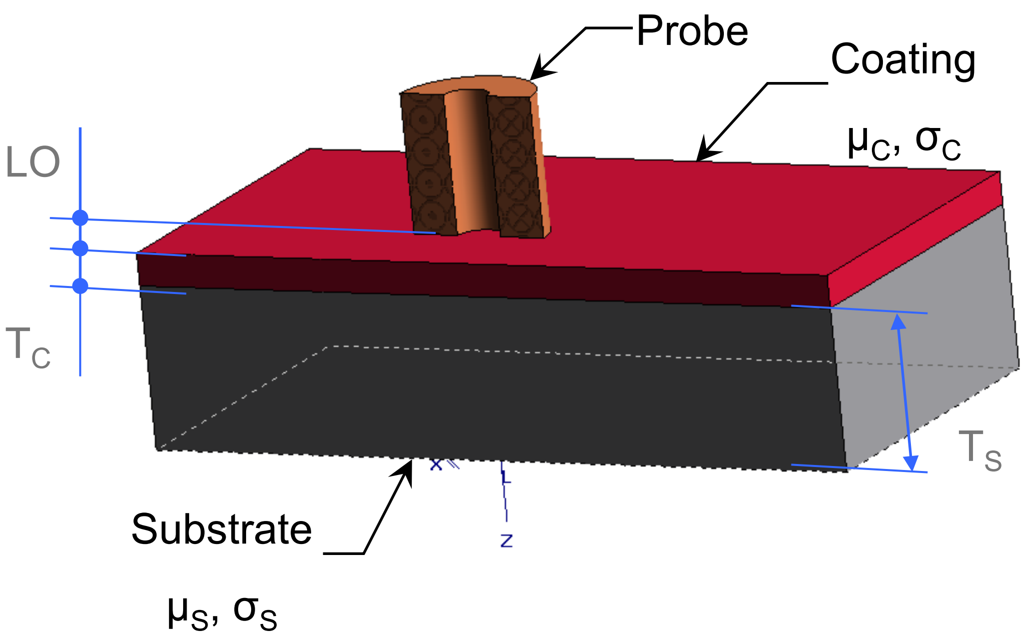


- Typical inspection tasks
  - Cracks, corrosion and other fabrication and service damage
- Renaissance of nuclear power plants will require more inspections
- Weld surface inspection

MOVIE TubInsp

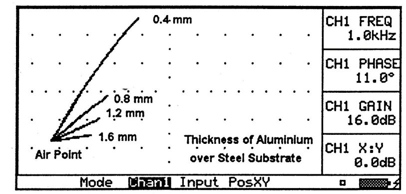
MOVIE TubInspDiffer

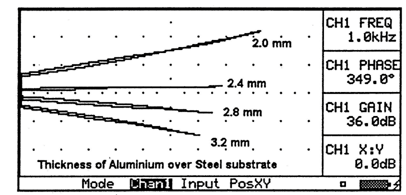
Main Applications of EC Testing – Coating Thickness



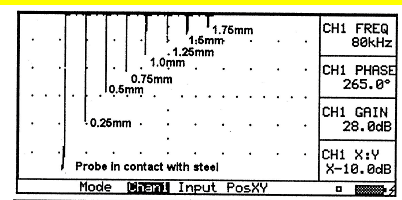
LO - Lift off
T_C – Coating thickness
T_S – Substrate thickness
μ_S, σ_S – magnetic permeability and electrical conductivity of substrate
μ_C, σ_C – magnetic permeability and electrical conductivity of coating

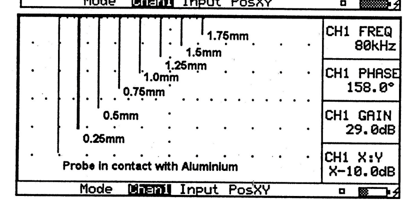
Aluminum Coating over Carbon Steel





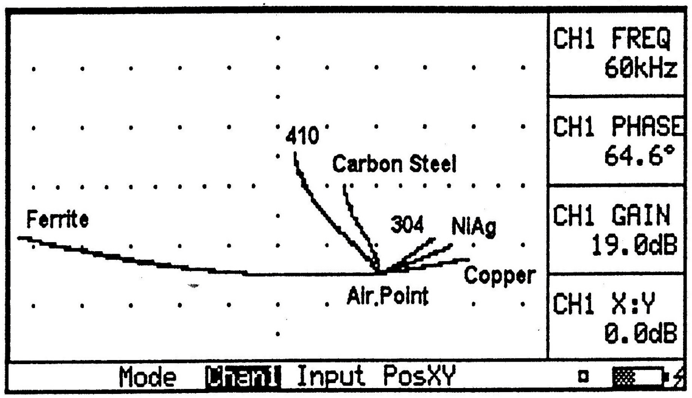
Paint over Aluminum and Carbon Steel



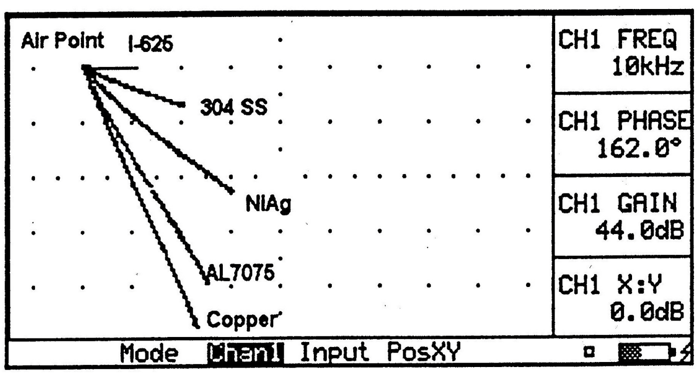


Main Applications of EC Testing – Material Sorting and Conductivity

Impedance Plane Indications



Sorting of Ferromagnetic and Nonferromagnetic Materials



Sorting of Nonferromagnetic Materials

Phasec D60 Manual

Set of Conductivity Specimens

- Common procedure for primary metal and automotive industries
- Performed manually, semi- or fully-automated
- Very reliable tool for heat treatment, case hardening depth, hardness, metal phase composition, stress and strain measurement and detection and other metal conditions

MOVIE Sorting

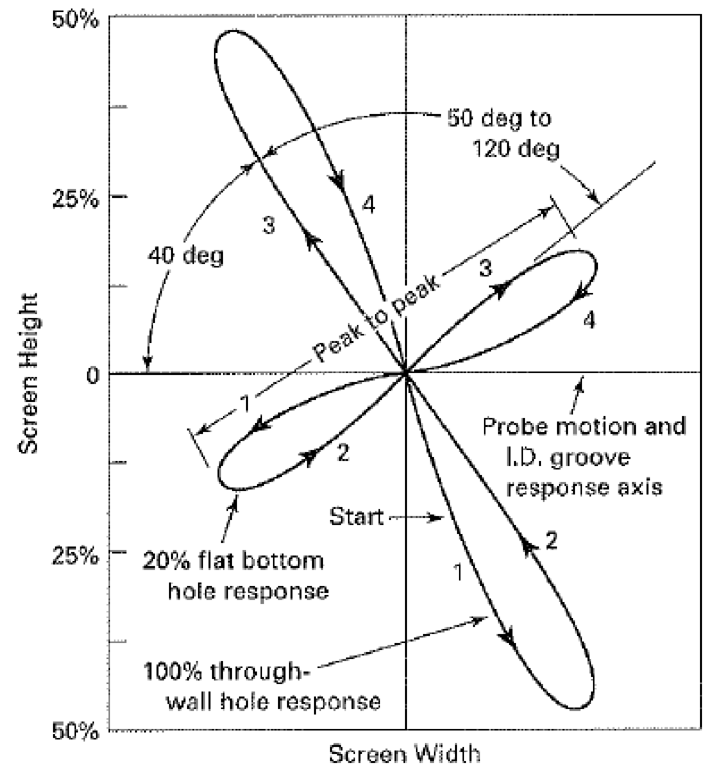
ASME Section V Requirements

- ASME Section V, Article 8, Eddy Current Examination
  - The section refers to different mandatory appendices depending on application
    - Appendix II, Eddy Current Examination of Nonferromagnetic Heat Exchanger Tubing
    - Appendix III, Eddy Current Examination on Coated Ferritic Materials
    - Appendix IV, External Coil Eddy Current Examination of Tubular Products
    - Appendix V, Eddy Current Measurement of Nonconductive-Nonmagnetic Coating Thickness on Nonmagnetic Metallic Material
    - Appendix VI, Eddy Current Detection and Measurement of Depth of Surface Discontinuities in Nonmagnetic Metals with Surface Probes
  - The format and requirements for all the appendices are similar
    - Only covering Appendix II in example

ASME Section V Requirements

- ASME Section V, Article 8, Appendix II, Eddy Current Examination of Nonferromagnetic Heat Exchanger Tubing
  - II-820, General Requirements
    - Lists the requirements for written procedures and procedure qualifications
  - II-830, Equipment
    - Describes different types of data acquisition systems and other equipment needed
  - II-840, Requirements
    - Include requirements for recording and sensitivity levels, probe speed, fixture location verification and automated eddy current data screens

FIG. II-860.3.1 DIFFERENTIAL TECHNIQUE RESPONSE FROM CALIBRATION REFERENCE STANDARD



ASME Section V Requirements

Requirement (as applicable)	Essential Variable	Nonessential Variable
Tube material	X	
Tube diameter and wall thickness	X	
Mode of inspection – differential or absolute	X	
Probe type and size	X	
Length of probe cable and probe extension cables	X	
Probe manufacture, part number, and description	X	
Examination frequencies, drive voltage, and gain settings	X	
Manufacturer and model of eddy current equipment	X	
Scanning direction during data recording, i.e., push or pull	X	
Scanning mode – manual, mechanized probe driver, remote controlled fixture	X	
Fixture location verification	X	

ASME Section V Requirements

Requirement (as applicable)	Essential Variable	Nonessential Variable
Identity of calibration reference standard(s)	X	
Minimum digitization rate	X	
Maximum scanning speed during data recording	X	
Personnel requirements		X
Data recording equipment manufacturer and model		X
Scanning speed during insertion or retraction, no data recording		X
Side of application – inlet or outlet		X
Data analysis parameters		X
Tube numbering		X
Tube examination surface preparation		X

ASME Section V Requirements

- ASME Section V, Article 8, Appendix II, Eddy Current Examination of Nonferromagnetic Heat Exchanger Tubing
  - II-860, Calibration
    - Covers the calibration requirements and reference standards
  - II-870, Examination
  - II-880, Evaluation
    - Covers the evaluation requirements and describes ways to determine flaw depth
  - II-890, Documentation
    - Defines indications and describes the minimum requirements for the examination record
      - Procedure used
      - Eddy current equipment used
      - Examination personnel
      - Record of indications
      - Date of examination

Advantages of Eddy Current Inspection

- Sensitive to small cracks and other defects
- Detects surface and near surface defects
- Inspection gives immediate results
- Equipment is very portable
- Method can be used for much more than flaw detection
- Minimum part preparation is required
- Test probe does not need to contact the part
- Inspects complex shapes and sizes of conductive materials

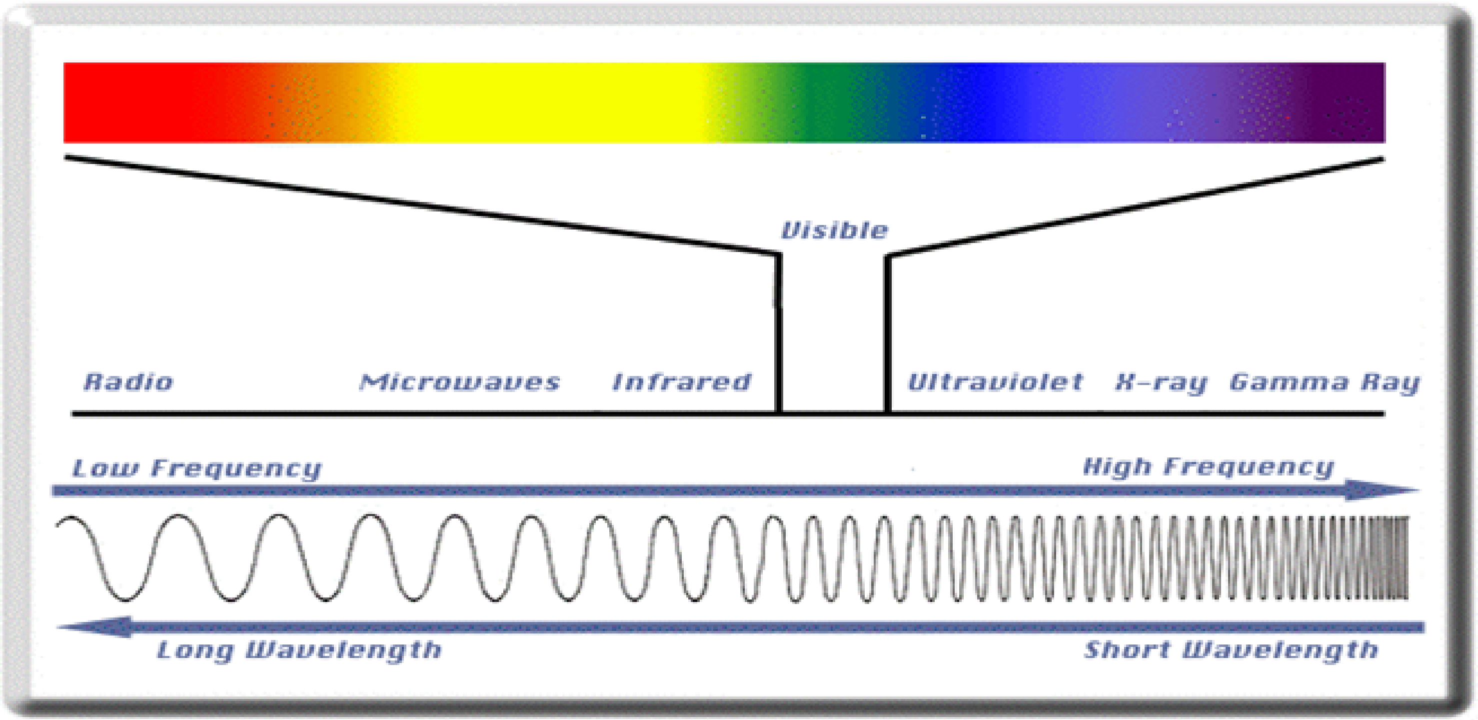
Limitations of Eddy Current Inspection

- Only conductive materials can be inspected
- Surface must be accessible to the probe
- Skill and training required is more extensive than other techniques
- Surface finish and roughness may interfere
- Reference standards needed for setup
- In general, depth of penetration is limited
- Flaws such as delaminations that lie parallel to the probe coil winding and probe scan direction are undetectable

Radiographic Testing

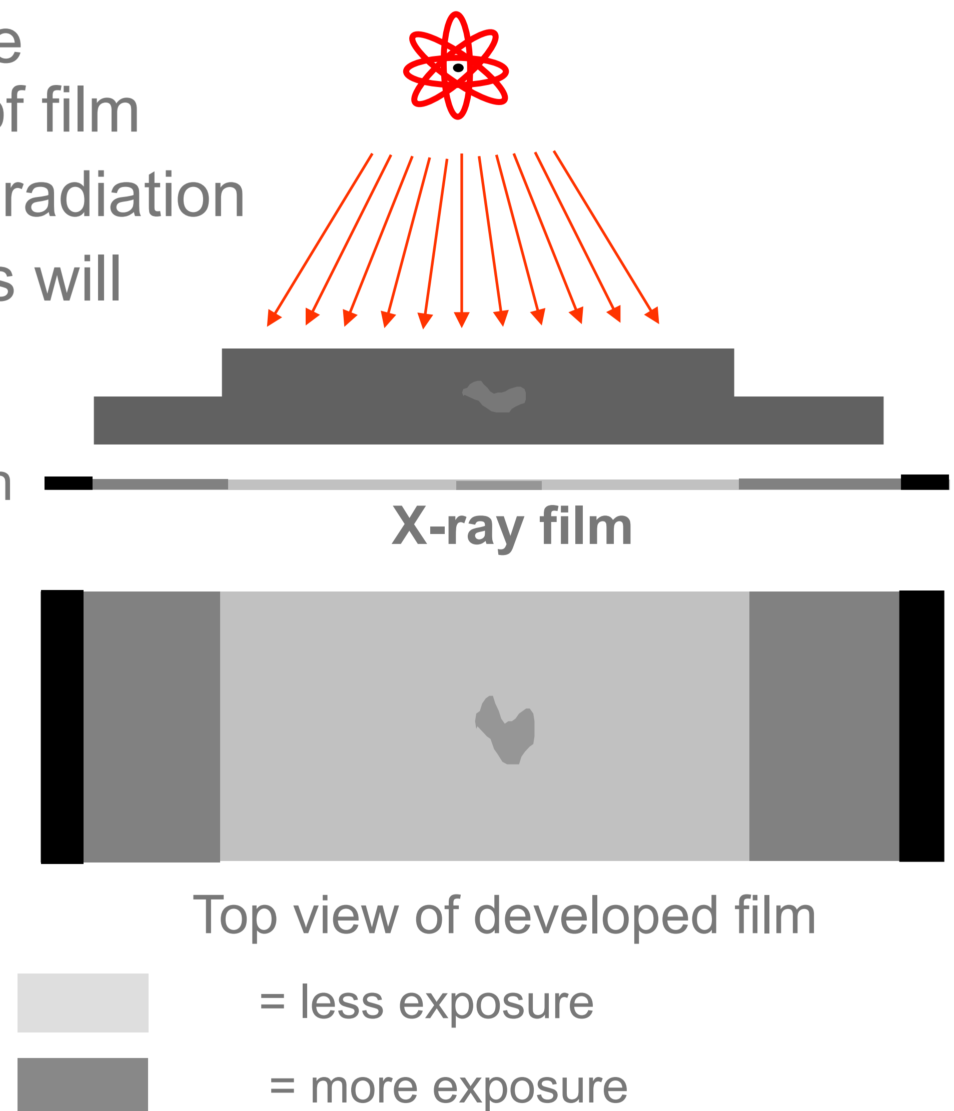
Module 6A.5

Electromagnetic Radiation



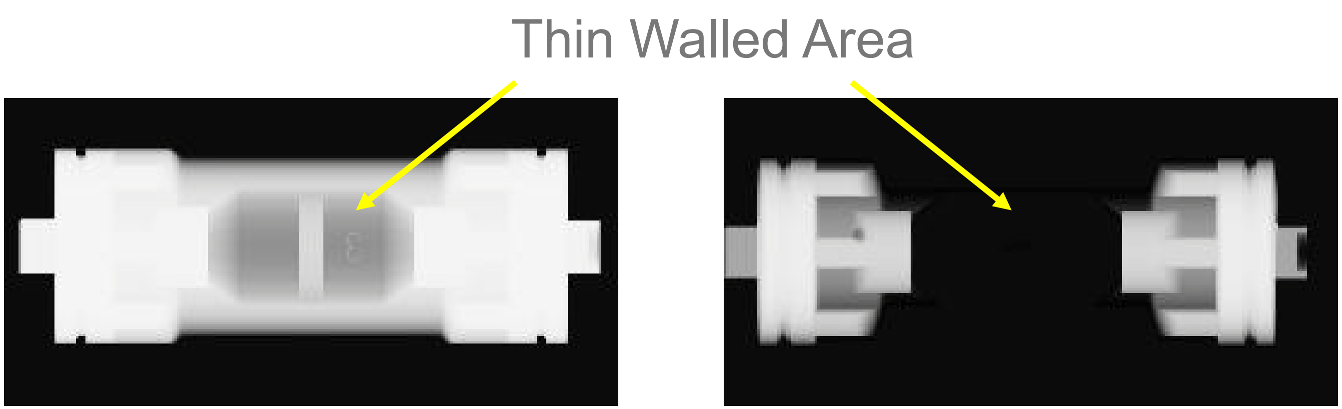
General Principles of Radiography

- The part is placed between the radiation source and a piece of film
- The part will stop some of the radiation
- Thicker and more dense areas will stop more of the radiation
  - The film darkness (density) will vary with the amount of radiation reaching the film through the test object



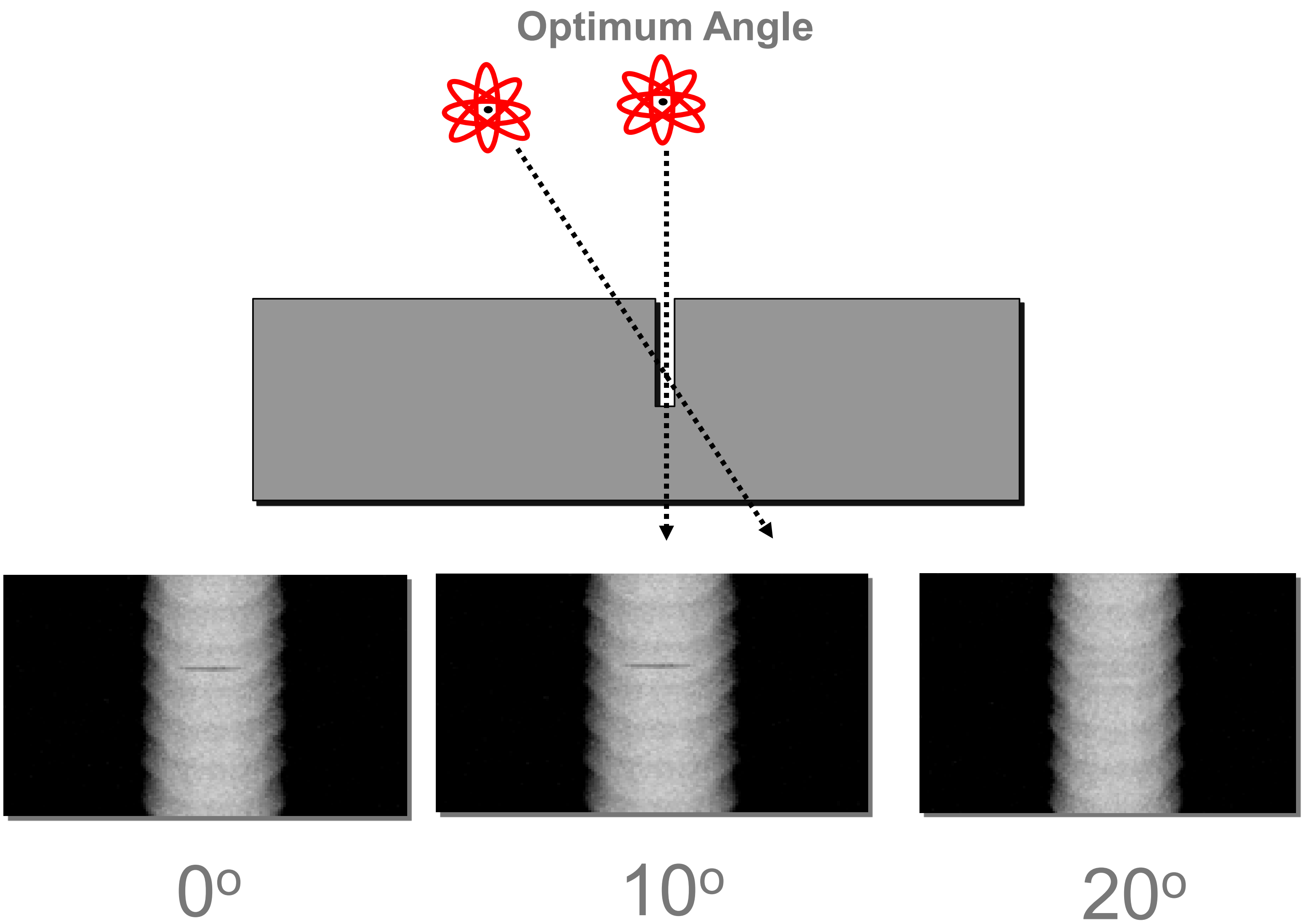
General Principles of Radiography

- The energy of the radiation affects its penetrating power
  - Higher energy radiation can penetrate thicker and more dense materials
- The radiation energy and/or exposure time must be controlled to properly image the region of interest



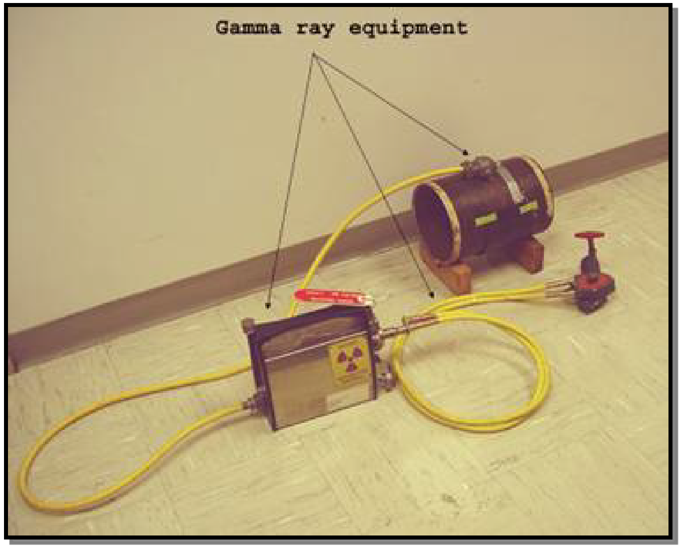
Low Energy Radiation   High Energy Radiation

Flaw Orientation

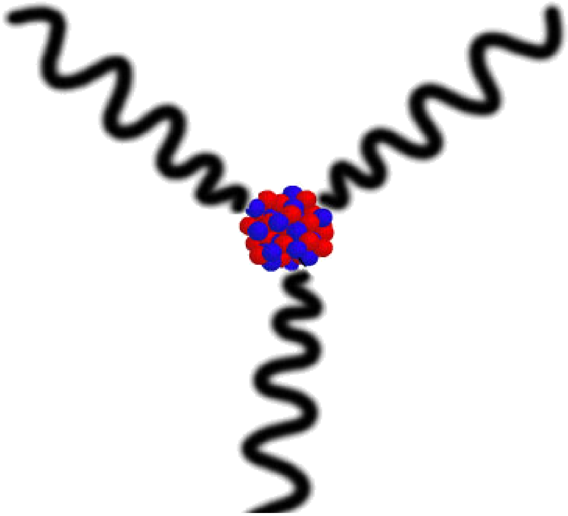


Radiation Sources

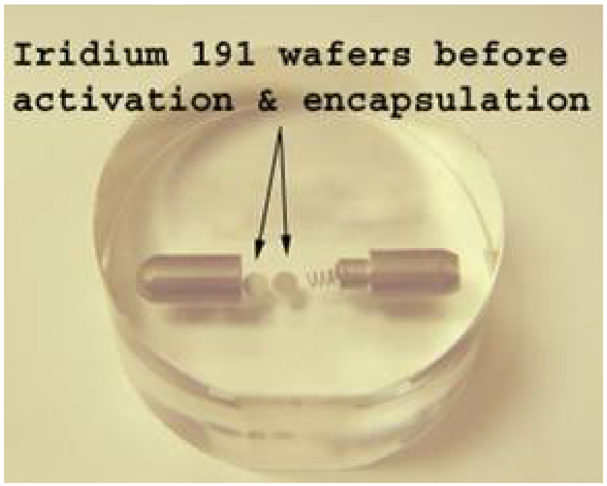
- Two of the most commonly used sources of radiation in industrial radiography are x-ray generators and gamma sources
- Industrial radiography is divided into X-ray radiography or gamma-radiography, depending on the source of radiation used

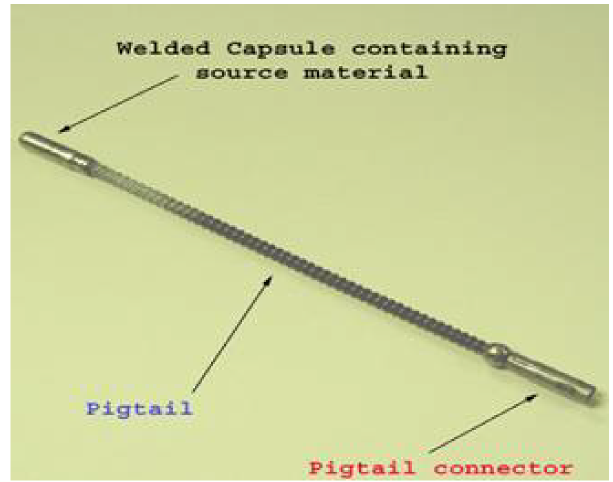


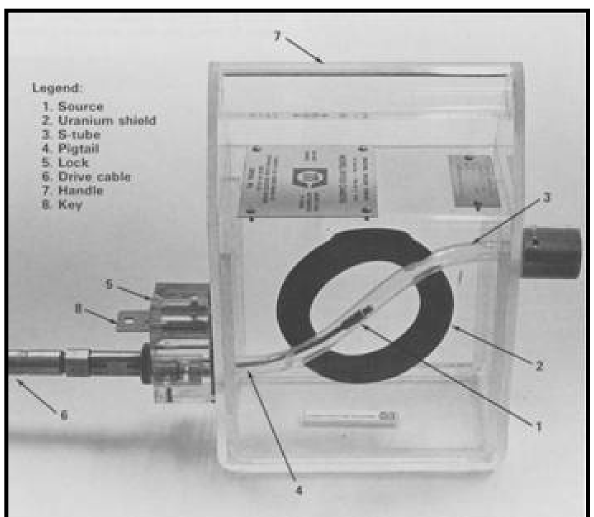
Gamma Radiography



Gamma Radiography

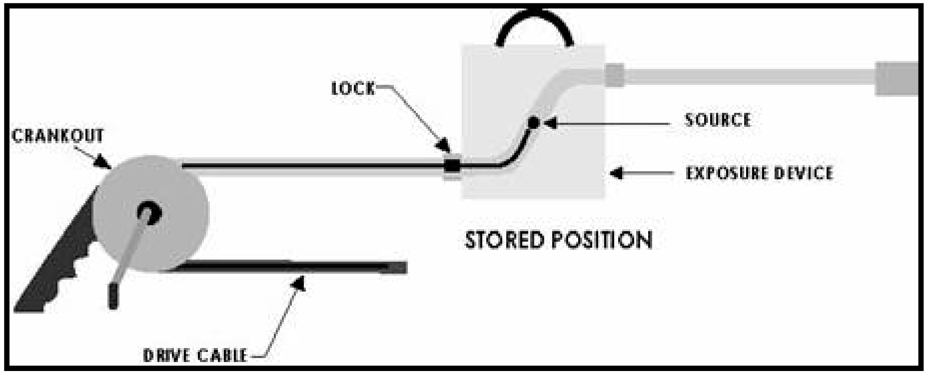




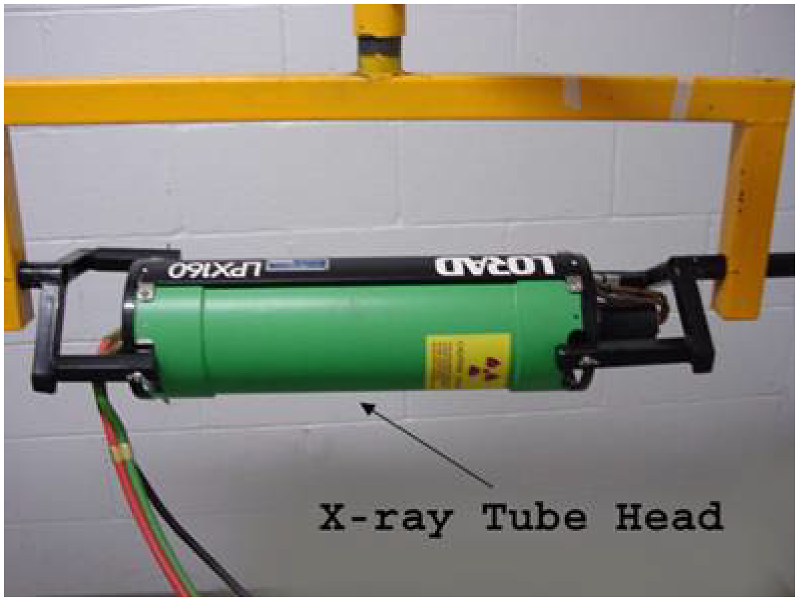


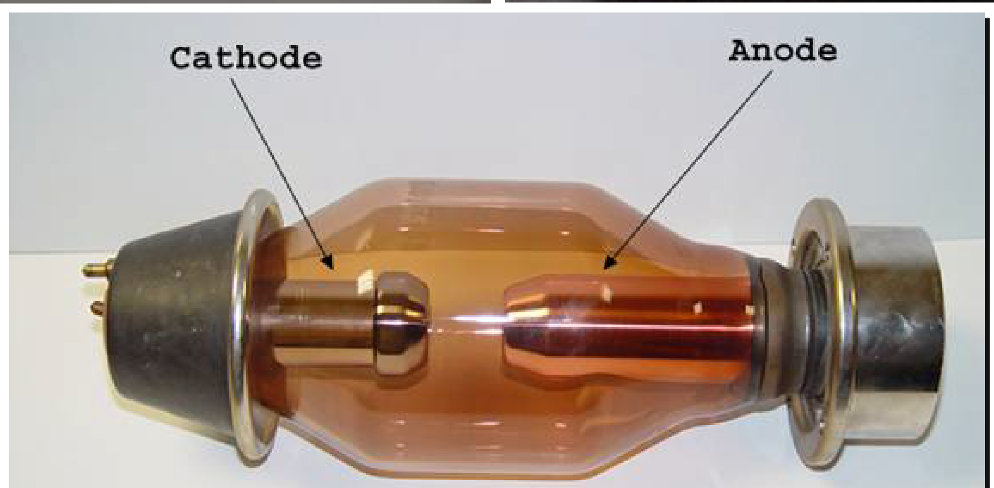
Gamma Radiography

- A drive cable is connected to the other end of the camera
- The drive cable, controlled by the radiographer, is used to force the radioactive material out into the guide tube where the gamma rays will pass through the specimen and expose the recording device



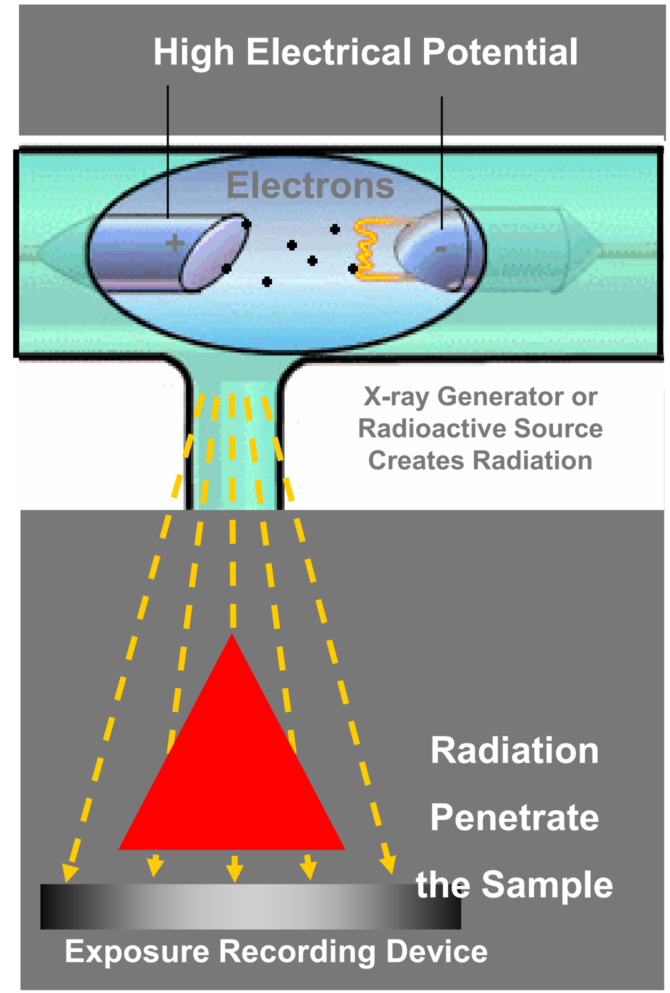
X-Ray Radiography





X-Ray Radiography

- The cathode contains a small filament much the same as in a light bulb
- Current passes through the filament which heats it, which causes electrons to be stripped off
- The high voltage causes these free electrons to be pulled toward a target material (usually made of tungsten) located in the anode
- The electrons impact against the target causing an energy exchange which creates x-rays

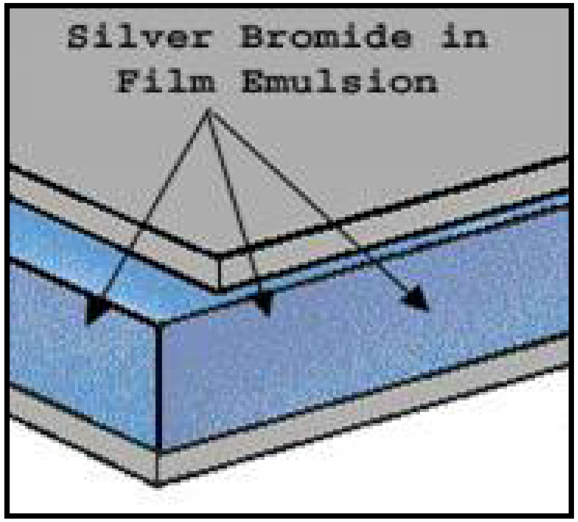


Imaging Modalities

- Several different imaging methods are available to display the final image in industrial radiography:
  - Film Radiography
  - Real Time Radiography (RTR)
  - Computed Radiography (CR)
  - Digital Radiography (DR)
  - Computed Tomography (CR)

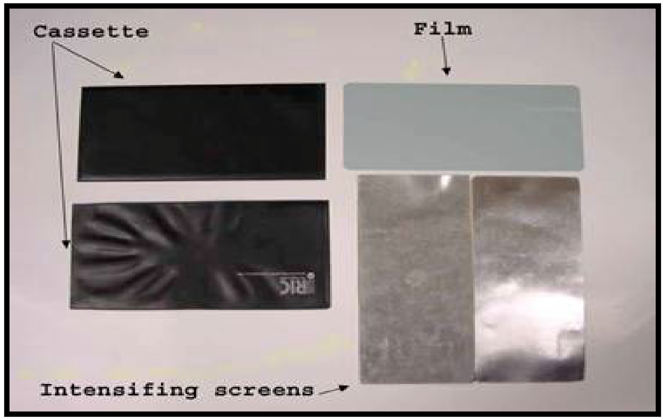
Film Radiography

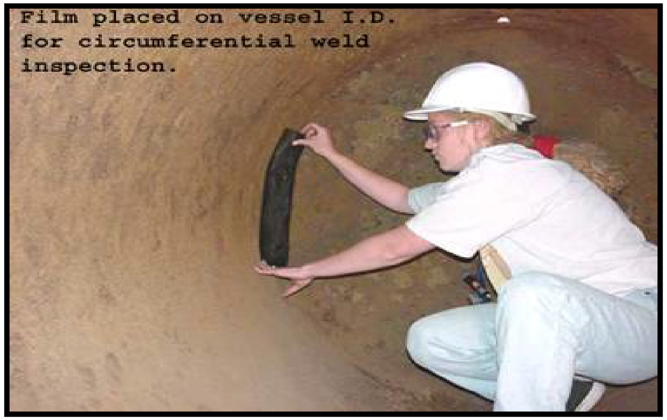
Photo Coutesy of AGFA-Gevaert Group

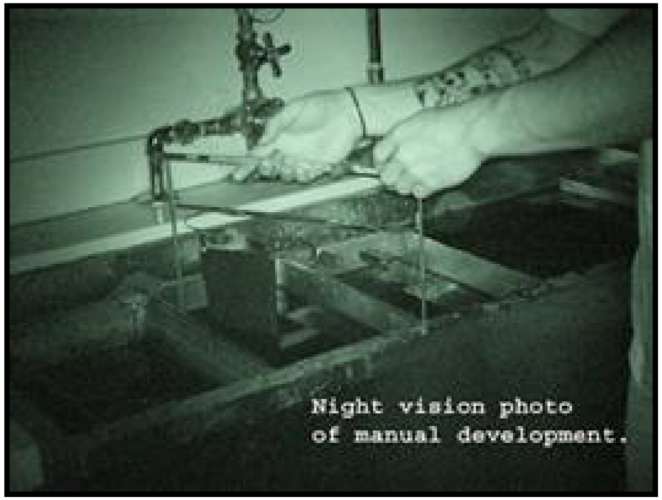


- One of the most widely used and oldest imaging mediums in industrial radiography is radiographic film
- Film contains microscopic material called silver bromide
- Once exposed to radiation and developed in a darkroom, silver bromide turns to black metallic silver, which forms the image

Film Radiography

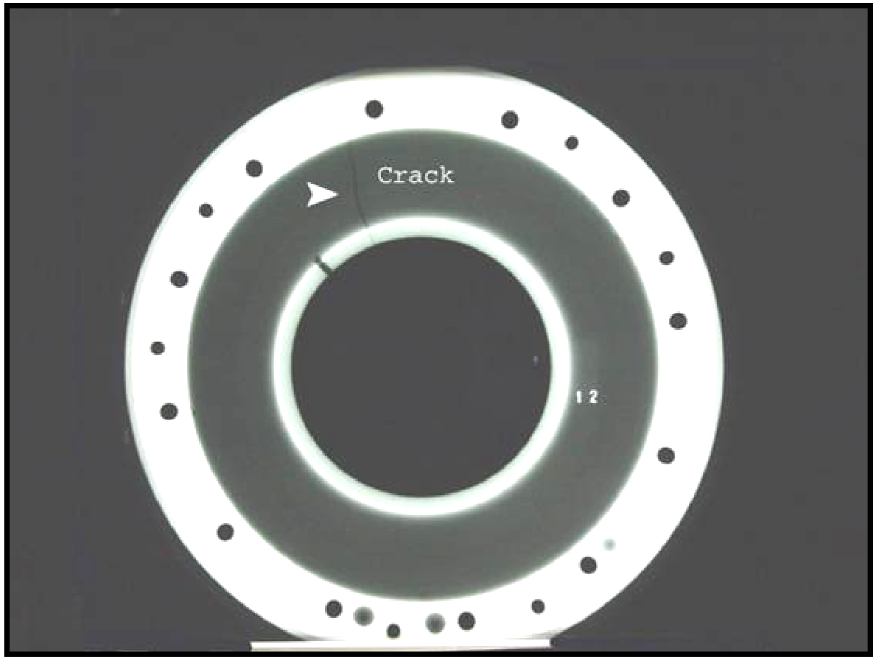


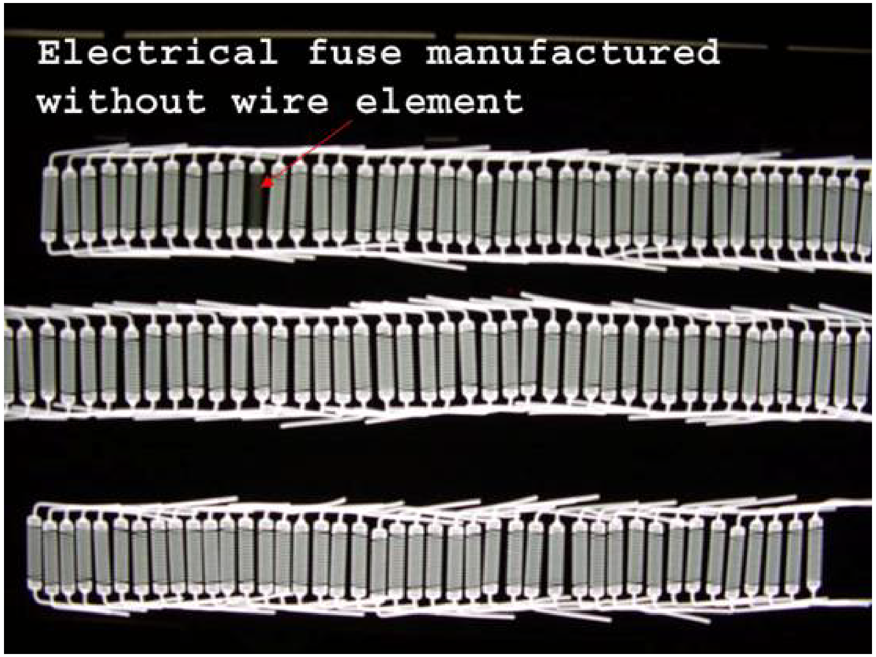




Film Radiography

Once developed, the film is referred to as a radiograph





Film Radiography

- The primary advantage of film radiography is high sensitivity
- There are several disadvantages
  - Typically longer exposure times than digital
  - Film processing time
  - Waste disposal issues associated with silver and the film processing chemicals
  - Storage of film
  - Degradation of film over time

Digital Radiography

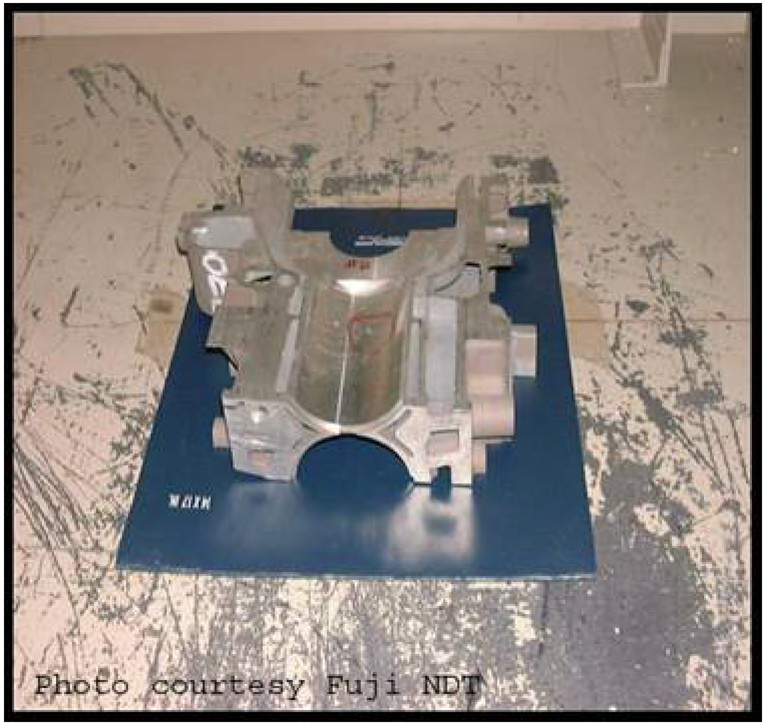
- One of the newest forms of radiographic imaging is Digital Radiography
- Requiring no film, digital radiographic images are captured using either special phosphor screens or flat panels containing micro-electronic sensors
- No darkrooms are needed to process film, and captured images can be digitally enhanced for increased detail
- Images are easily archived when in digital form

Digital Radiography

- Advantages
  - Lower radiation levels required
  - Image can be digitally enhanced to help with interpretation
  - No degradation of image over time
  - Ease of storage
- Disadvantages
  - Typically lower sensitivity than film
  - Fear factor of changing

Computed Radiography

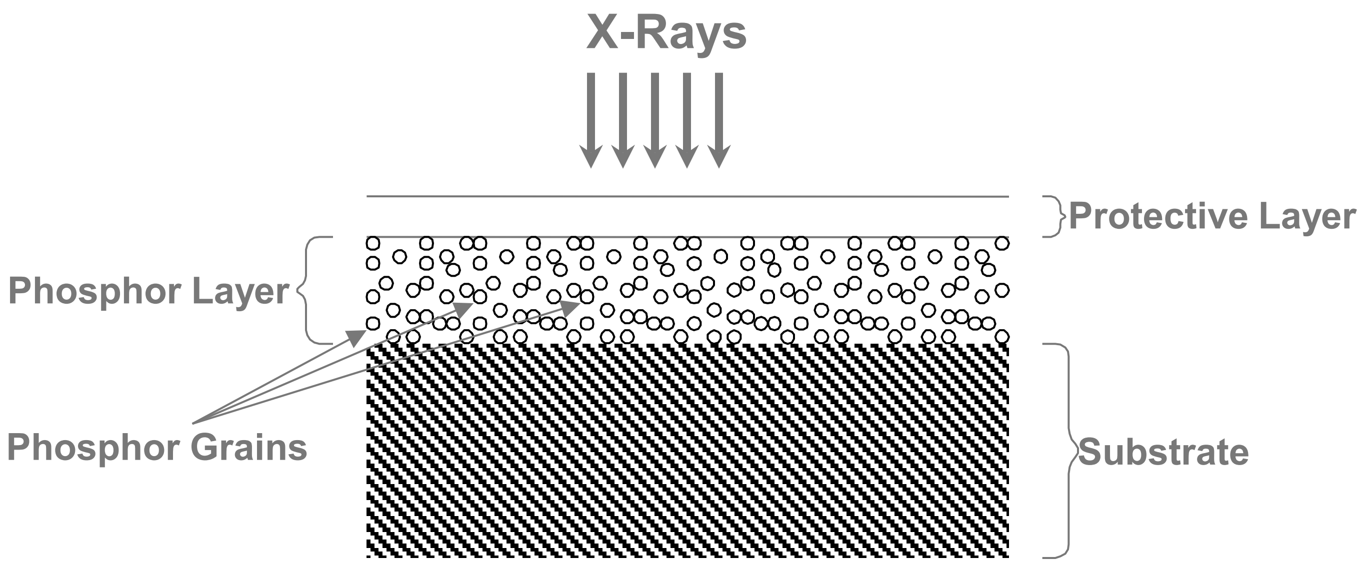
Computed Radiography (CR) is a digital imaging process that uses a phosphor imaging plate (PIP) instead of film



Computed Radiography

- X-rays penetrating the specimen stimulate the phosphors
- The stimulated phosphors remain in an excited state

CR Phosphor Screen Structure

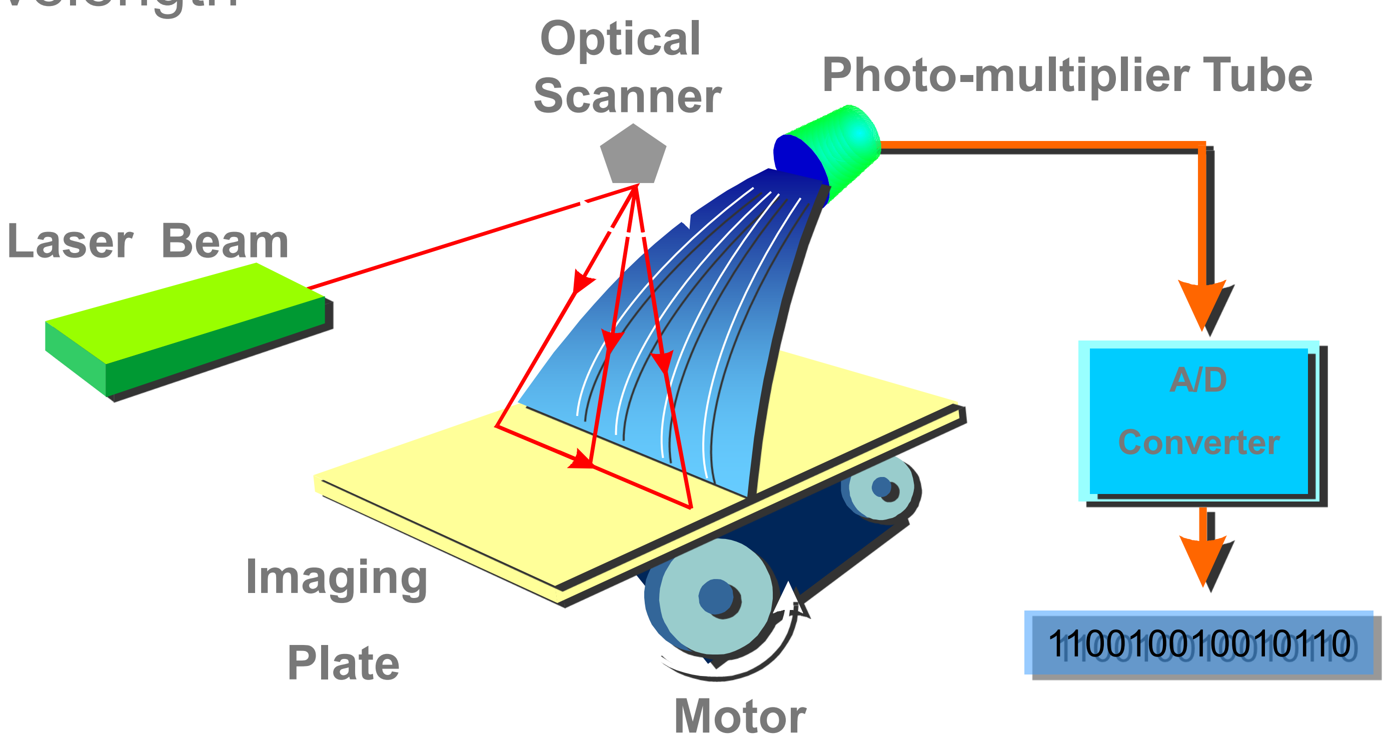


Computed Radiography

- After exposure the imaging plate is read electronically and erased (via natural light) for re-use in a special scanner system

Computed Radiography

- Technique possible due to photostimulable luminescence (PSL)
- PSL is a phenomenon in which a phosphor that has ceased emitting light, because of the removal of the stimulus, once again emits light when excited by light with a longer wavelength



Computed Radiography

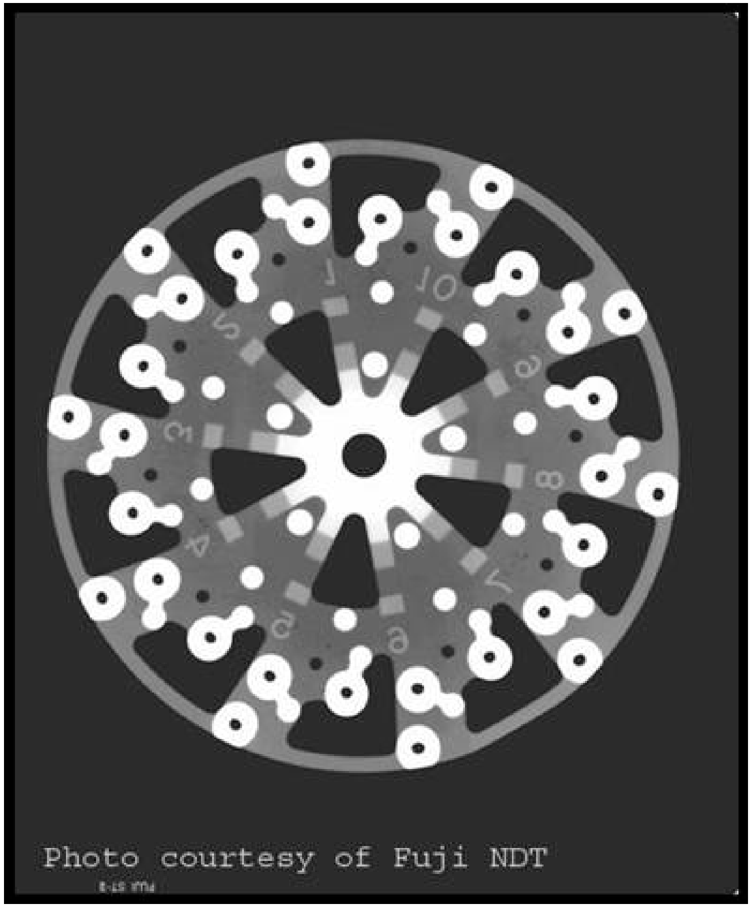
- Digital images are typically sent to a computer workstation where specialized software allows manipulation and enhancement

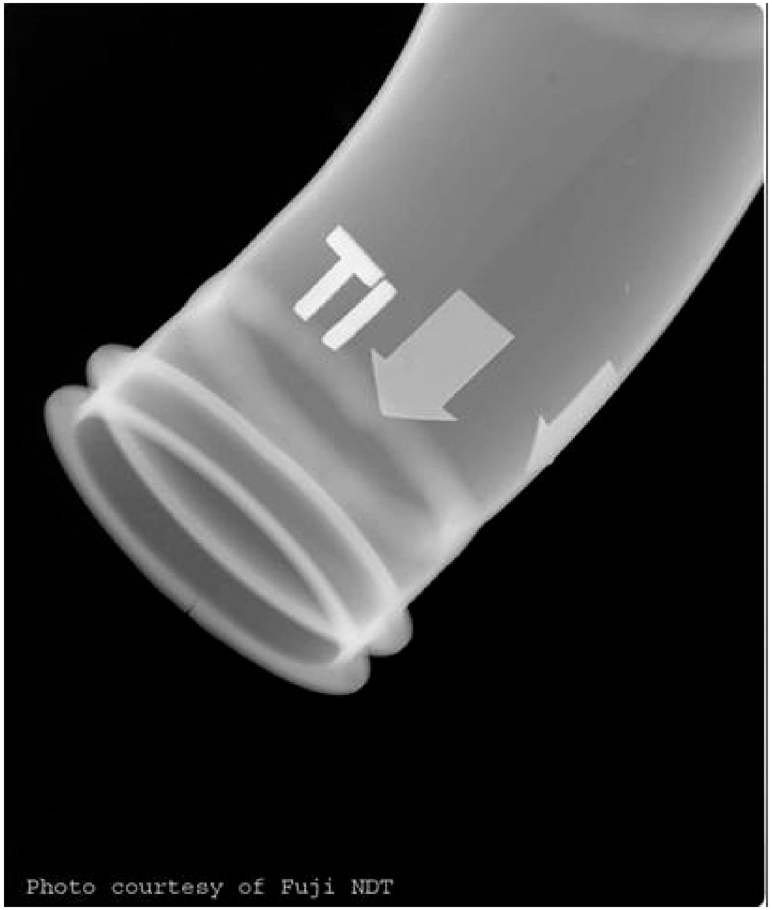
Photo courtesy of Fuji NDT


Photo courtesy of Fuji NDT

Computed Radiography

- Examples of computed radiographs:



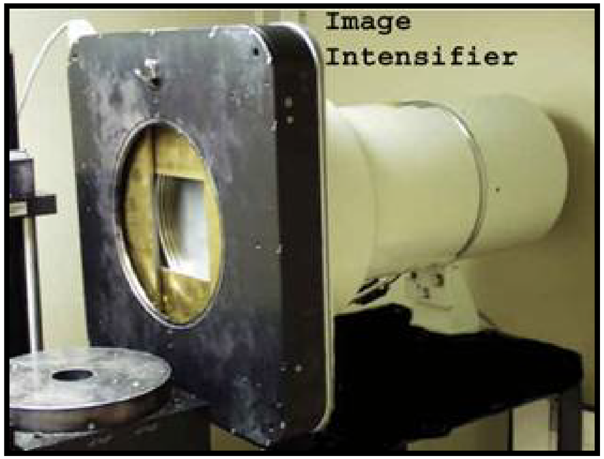


Real-Time Radiography

- The equipment needed for Real-Time Radiography (RTR) includes:
  - X-ray tube
  - Image intensifier or other real-time detector
  - Camera
  - Computer with frame grabber board and software
  - Monitor
  - Sample positioning system (optional)

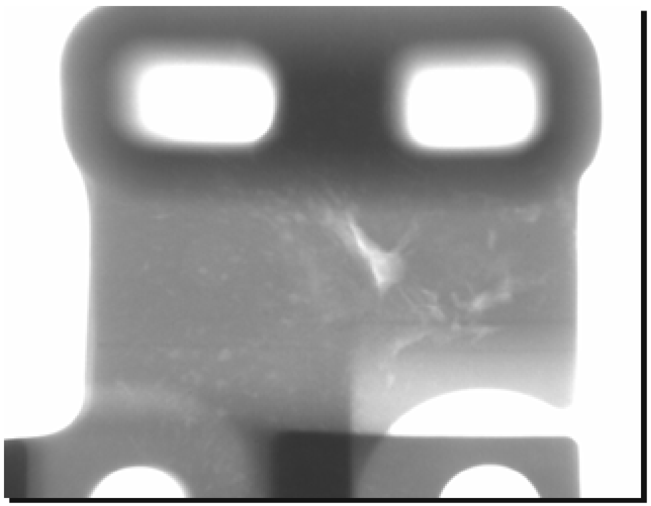
Real-Time Radiography

- The image intensifier is a device that converts the radiation that passes through the specimen into light
- It uses materials that fluoresce when struck by radiation
- The more radiation that reaches the input screen, the more light that is given off
- The image is very faint on the input screen so it is intensified onto a small screen inside the intensifier where the image is viewed with a camera

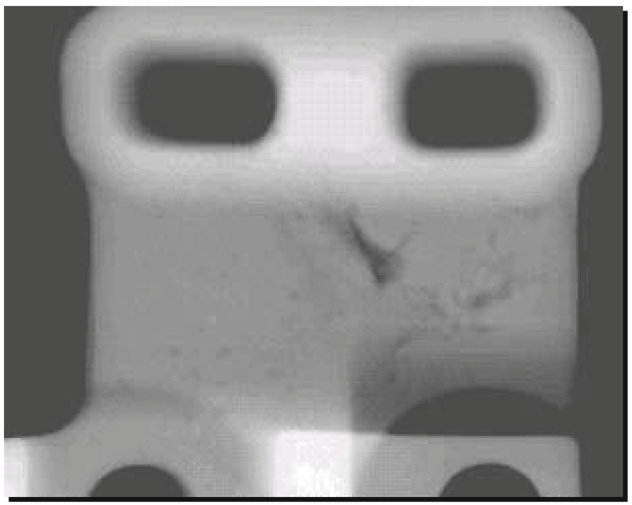


Real-Time Radiography

- Comparing Film and Real-Time Radiography



<u>Real-time</u> images are lighter in areas where more X-ray photons reach and excite the fluorescent screen.



<u>Film images</u> are darker in areas where more X-ray photons reach and ionize the silver molecules in the film.

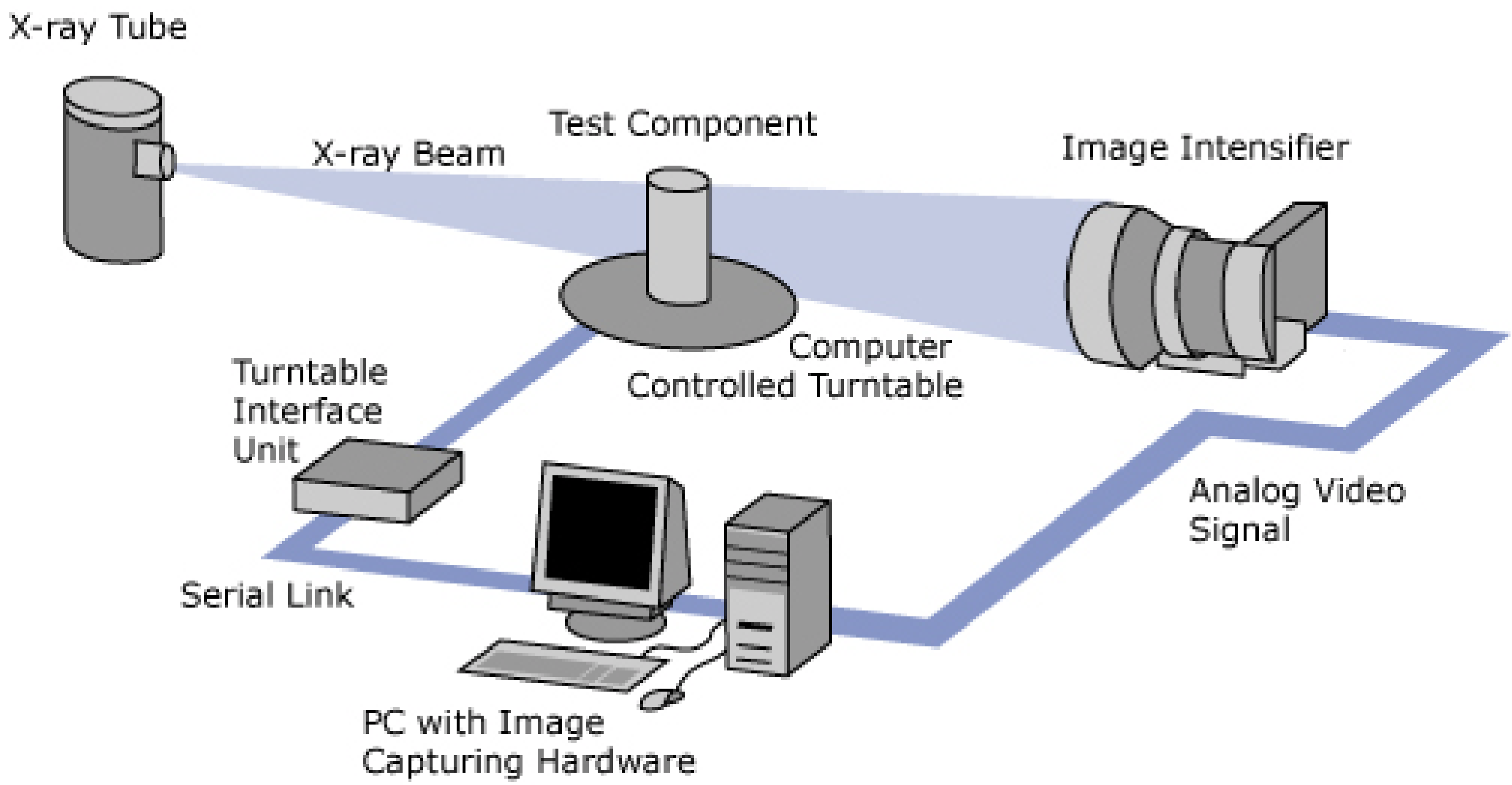
Direct Radiography

- Direct radiography (DR) is a form of real-time radiography that uses a special flat panel detector
- The panel works by converting penetrating radiation passing through the test specimen into minute electrical charges
- The panel contains many micro-electronic capacitors
- The capacitors form an electrical charge pattern image of the specimen
  - Each capacitor's charge is converted into a pixel which forms the image

Image courtesy AFGA NDT

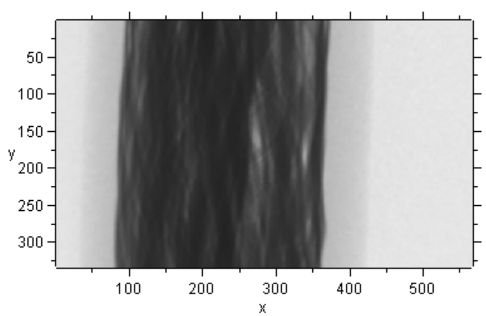
Computed Tomography

- Computed Tomography (CT) uses a real-time inspection system employing a sample positioning system and special software

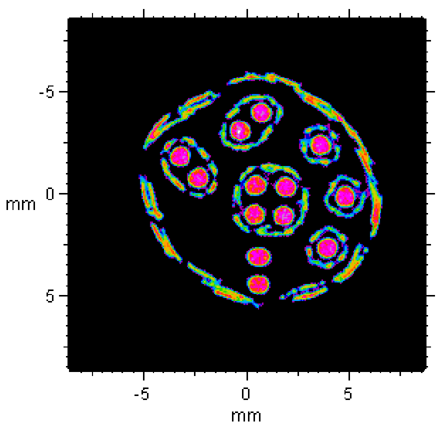


Computed Tomography

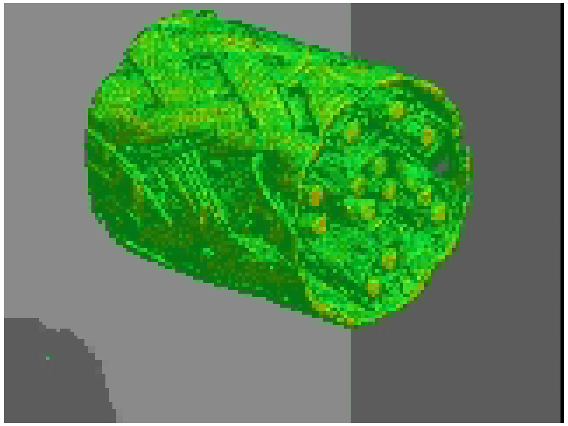
- Many separate images are saved and complied into 2-dimensional sections as the sample is rotated
- 2-D images are then combined into 3-D images
- Known as a CT or CAT scan in the medical field



Real-Time Captures

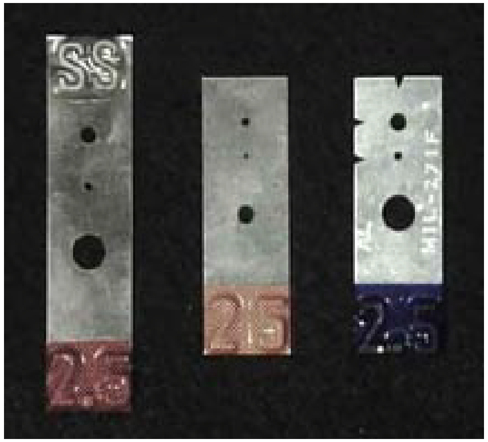


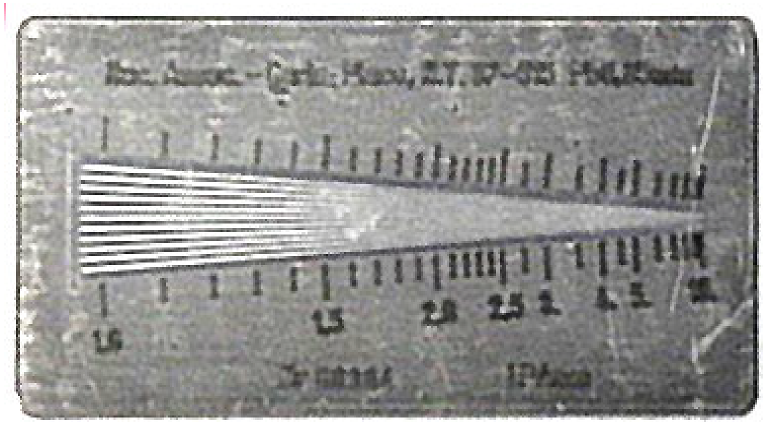
Compiled 2-D Images

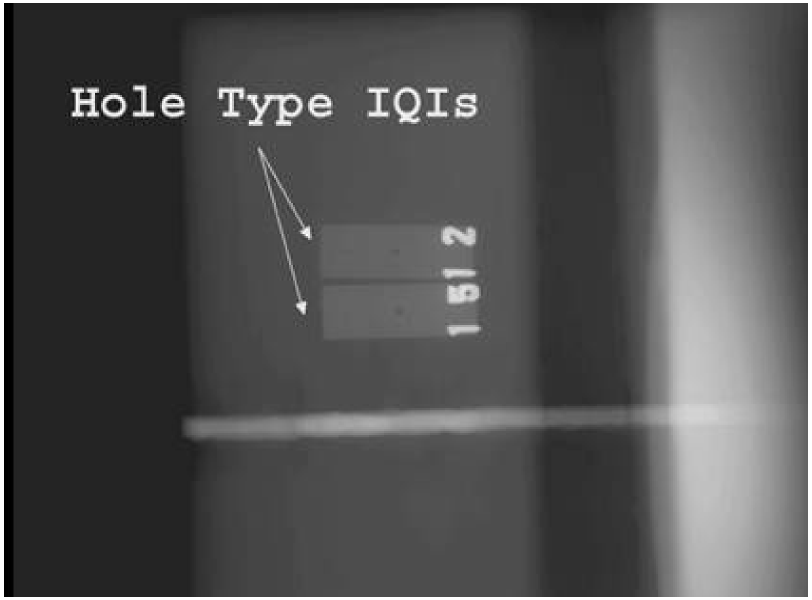


Compiled 3-D Structure

Image Quality







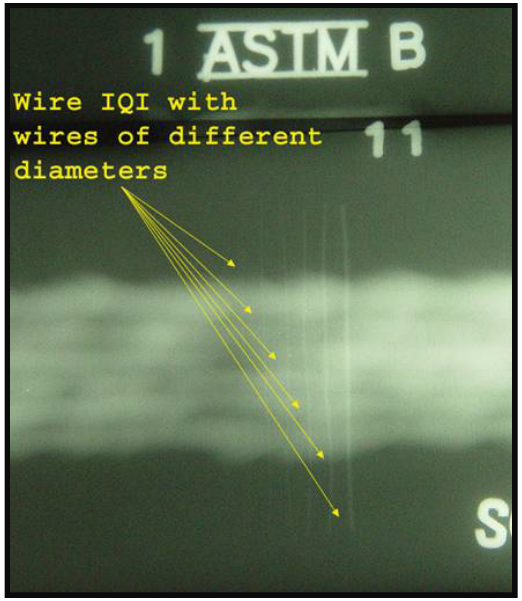
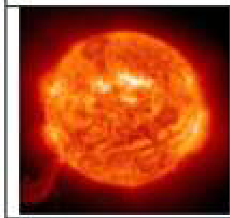
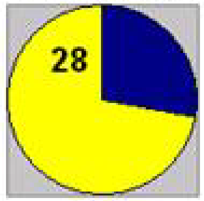
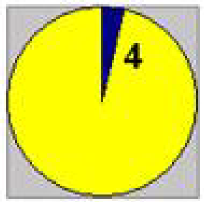
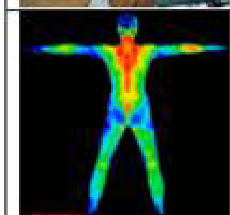
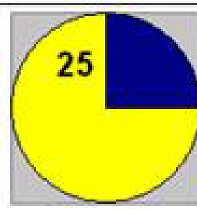
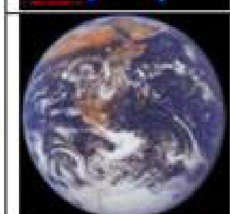
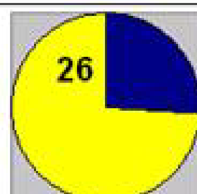
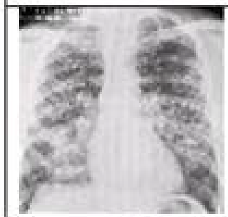
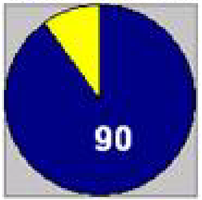
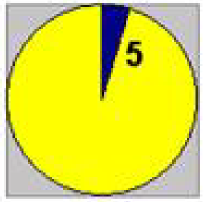
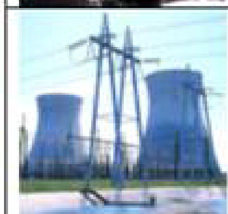
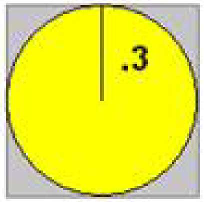
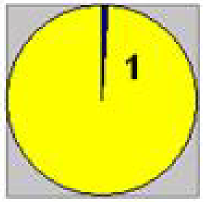


Image Quality

- Image quality for plaque IQIs is given as a combination of hole size and IQI thickness relative to the part thickness
- 2-2T is a common sensitivity level requirement
  - This means that a plaque IQI having a thickness that is 2% of the part thickness shall be used and the IQI hole diameter that is 2 times the IQI thickness shall be visible in the radiograph
- ASTM E747 provides “equivalent penetrameter sensitivity” (EPS) levels for plaque IQIs and wire IQIs

Radiation Safety

Natural Sources		Annual Dose (mrem/year)
	Cosmic rays (radiation from the sun and outer space)	 28
	Building materials	 4
	The human body	 25
	The earth	 26

Manmade Sources		Annual Dose (mrem/year)
	Medical (primarily from diagnostic X-rays)	 90
	Fallout from atomic bombs	 5
	Nuclear power production	 .3
	Consumer products (mostly from color TV sets)	 1

Radiation Safety

Technicians who work with radiation must wear monitoring devices that keep track of their total absorption, and alert them when they are in a high radiation area.


Survey Meter

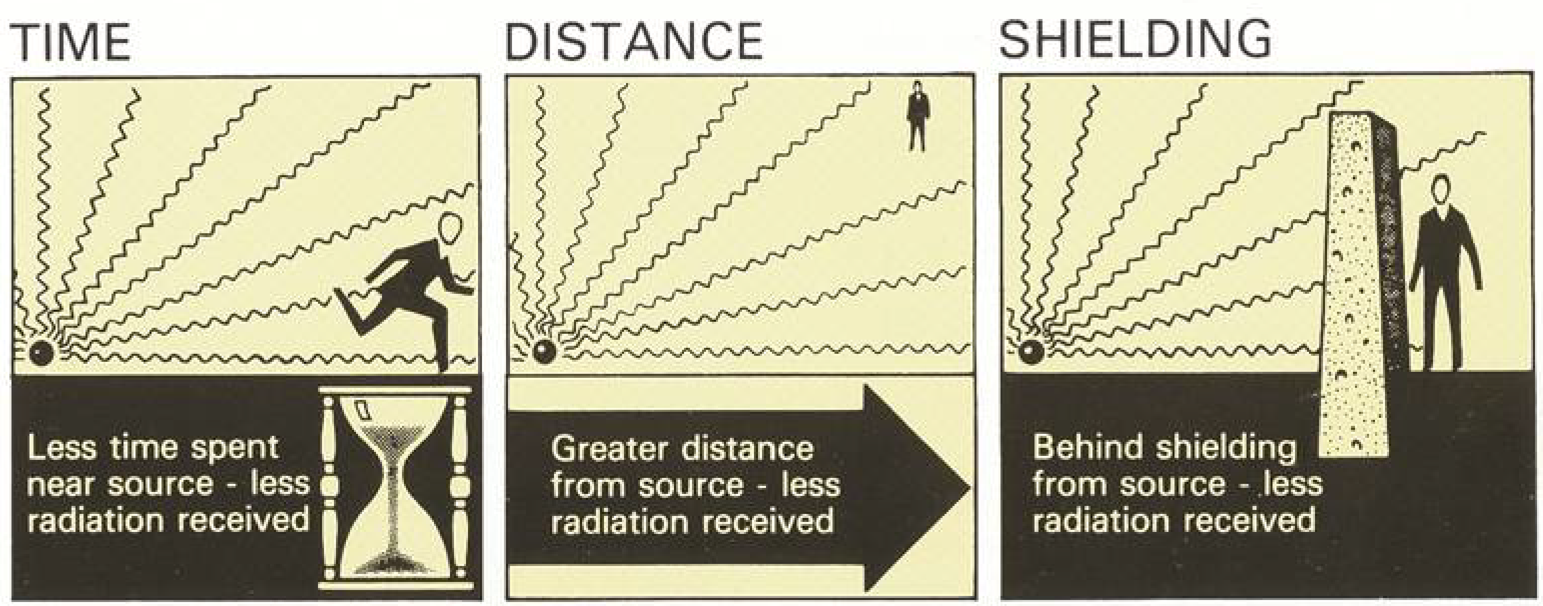

Pocket Dosimeter

Radiation Alarm

Radiation Badge

Radiation Safety

- There are three means of protection to help reduce exposure to radiation
  - Time
  - Distance
  - Shielding



ASME Section V Requirements

- ASME Section V, Article 2, Radiographic Examination
  - The section refers to different mandatory appendices depending on application
    - Appendix I, In-Motion Radiography
    - Appendix II, Real-Time Radioscopic Examination
    - Appendix III, Digital Image Acquisition, Display, and Storage for Radiography and Radioscopy
    - Appendix IV, Interpretation, Evaluation, and Disposition of Radiographic and Radioscopic Examination Test Results Produced by the Digital Image Acquisition and Display Process
    - Appendix VI, Digital Image Acquisition, Display, Interpretation, and Storage of Radiographs for Nuclear Applications
    - Appendix VII, Radiographic Examination of Metallic Castings
    - Appendix VIII, Radiography using Phosphor Imaging Plate
    - Appendix IX, Application of Digital Radiography
  - There is a nonmandatory appendix the provides recommendations of radiographic techniques for pipe or tube welds

ASME Section V Requirements

- ASME Section V, Article 2, Radiographic Examination
  - T-220, General Requirements
    - Lists the requirements for written procedures, procedure qualifications, procedure demonstration, surface preparation, and backscatter radiation
    - There are a minimum of seven requirements for a procedure
      - Material and thickness range
      - Isotope or maximum x-ray voltage
      - Source to object distance
      - Source size
      - Film brand and designation
      - Screens used
  - T-230, Equipment and Materials
    - Describes different types of equipment needed
      - Specifies Image Quality Indicator (IQI) designs should be hole or wire type or equivalent

TABLE T-233.2
WIRE IQI DESIGNATION, WIRE DIAMETER, AND WIRE IDENTITY

Set A			Set B		
Wire Diameter, in.	(mm)	Wire Identity	Wire Diameter, in.	(mm)	Wire Identity
0.0032	(0.08)	1	0.010	(0.25)	6
0.004	(0.10)	2	0.013	(0.33)	7
0.005	(0.13)	3	0.016	(0.41)	8
0.0063	(0.16)	4	0.020	(0.51)	9
0.008	(0.20)	5	0.025	(0.64)	10
0.010	(0.25)	6	0.032	(0.81)	11

Set C			Set D		
Wire Diameter, in.	(mm)	Wire Identity	Wire Diameter, in.	(mm)	Wire Identity
0.032	(0.81)	11	0.100	(2.54)	16
0.040	(1.02)	12	0.126	(3.20)	17
0.050	(1.27)	13	0.160	(4.06)	18
0.063	(1.60)	14	0.200	(5.08)	19
0.080	(2.03)	15	0.250	(6.35)	20
0.100	(2.54)	16	0.320	(8.13)	21

ASME Section V Requirements

TABLE T-233.1
HOLE-TYPE IQI DESIGNATION, THICKNESS, AND HOLE DIAMETERS

IQI Designation	IQI Thickness, in. (mm)	1*T* Hole Diameter, in. (mm)	2*T* Hole Diameter, in. (mm)	4*T* Hole Diameter, in. (mm)
5	0.005 (0.13)	0.010 (0.25)	0.020 (0.51)	0.040 (1.02)
7	0.0075 (0.19)	0.010 (0.25)	0.020 (0.51)	0.040 (1.02)
10	0.010 (0.25)	0.010 (0.25)	0.020 (0.51)	0.040 (1.02)
12	0.0125 (0.32)	0.0125 (0.32)	0.025 (0.64)	0.050 (1.27)
15	0.015 (0.38)	0.015 (0.38)	0.030 (0.76)	0.060 (1.52)
17	0.0175 (0.44)	0.0175 (0.44)	0.035 (0.89)	0.070 (1.78)
20	0.020 (0.51)	0.020 (0.51)	0.040 (1.02)	0.080 (2.03)
25	0.025 (0.64)	0.025 (0.64)	0.050 (1.27)	0.100 (2.54)
30	0.030 (0.76)	0.030 (0.76)	0.060 (1.52)	0.120 (3.05)
35	0.035 (0.89)	0.035 (0.89)	0.070 (1.78)	0.140 (3.56)
40	0.040 (1.02)	0.040 (1.02)	0.080 (2.03)	0.160 (4.06)
45	0.045 (1.14)	0.045 (1.14)	0.090 (2.29)	0.180 (4.57)
50	0.050 (1.27)	0.050 (1.27)	0.100 (2.54)	0.200 (5.08)
60	0.060 (1.52)	0.060 (1.52)	0.120 (3.05)	0.240 (6.10)
70	0.070 (1.78)	0.070 (1.78)	0.140 (3.56)	0.280 (7.11)
80	0.080 (2.03)	0.080 (2.03)	0.160 (4.06)	0.320 (8.13)
100	0.100 (2.54)	0.100 (2.54)	0.200 (5.08)	0.400 (10.16)
120	0.120 (3.05)	0.120 (3.05)	0.240 (6.10)	0.480 (12.19)
140	0.140 (3.56)	0.140 (3.56)	0.280 (7.11)	0.560 (14.22)
160	0.160 (4.06)	0.160 (4.06)	0.320 (8.13)	0.640 (16.26)
200	0.200 (5.08)	0.200 (5.08)	0.400 (10.16)	. . .
240	0.240 (6.10)	0.240 (6.10)	0.480 (12.19)	. . .
280	0.280 (7.11)	0.280 (7.11)	0.560 (14.22)	. . .

ASME Section V Requirements

- ASME Section V, Article 2, Radiographic Examination
  - T-260, Calibration
    - Lists the calibration requirements including verifying the source size and densitometer or step wedge comparison file
  - T-270, Examination
    - Covers the different methods and requirements for examination
      - T-271.1, Single-Wall Technique
      - T-271.2, Double-Wall Technique
      - T-274, Geometric Unsharpness
      - T-275, Location Markers
      - T-276, IQI Selection

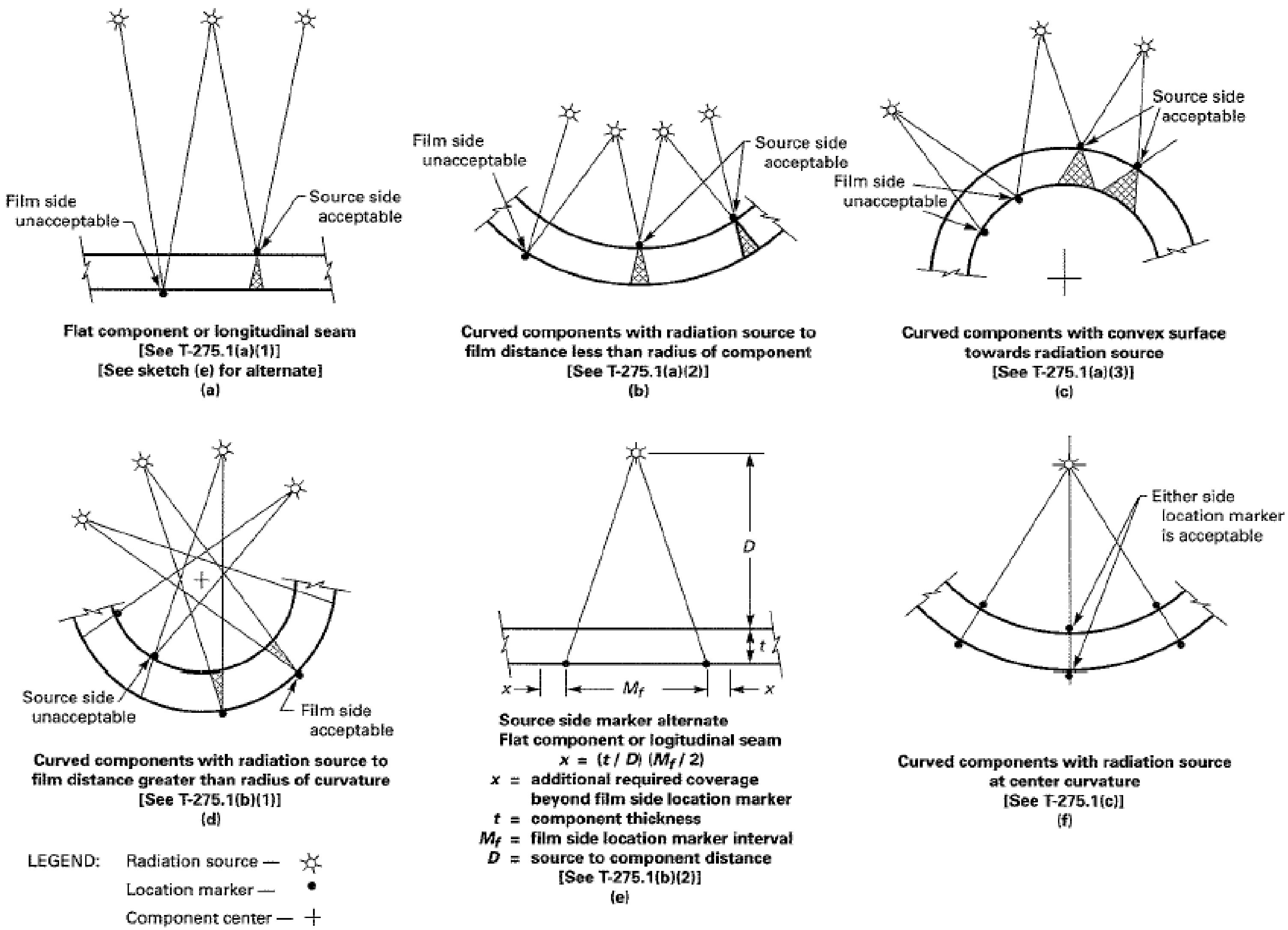
T-274.2 Geometric Unsharpness Limitations. Recommended maximum values for geometric unsharpness are as follows:

Material Thickness, in. (mm)	U_g Maximum, in. (mm)
Under 2 (50)	0.020 (0.51)
2 through 3 (50–75)	0.030 (0.76)
Over 3 through 4 (75–100)	0.040 (1.02)
Greater than 4 (100)	0.070 (1.78)

NOTE: Material thickness is the thickness on which the IQI is based.

ASME Section V Requirements

FIG. T-275 LOCATION MARKER SKETCHES



Flat component or longitudinal seam
[See T-275.1(a)(1)]
[See sketch (e) for alternate]
(a)

Curved components with radiation source to film distance less than radius of component
[See T-275.1(a)(2)]
(b)

Curved components with convex surface towards radiation source
[See T-275.1(a)(3)]
(c)

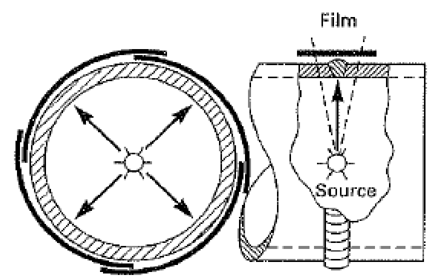
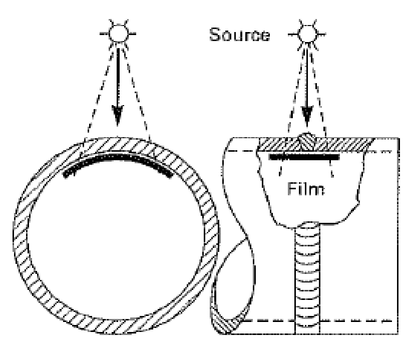
Curved components with radiation source to film distance greater than radius of curvature
[See T-275.1(b)(1)]
(d)

Source side marker alternate
Flat component or logitudinal seam
$x = (t / D)(M_f / 2)$
x = additional required coverage beyond film side location marker
t = component thickness
M_f = film side location marker interval
D = source to component distance
[See T-275.1(b)(2)]
(e)

Curved components with radiation source at center curvature
[See T-275.1(c)]
(f)

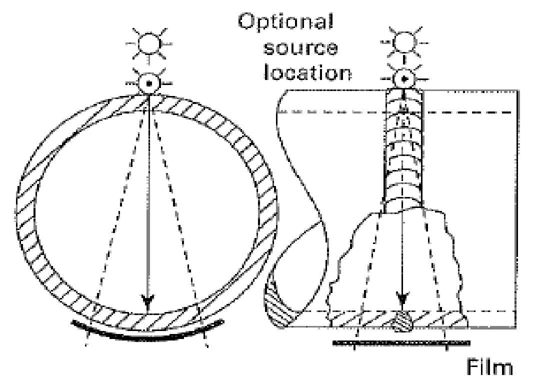
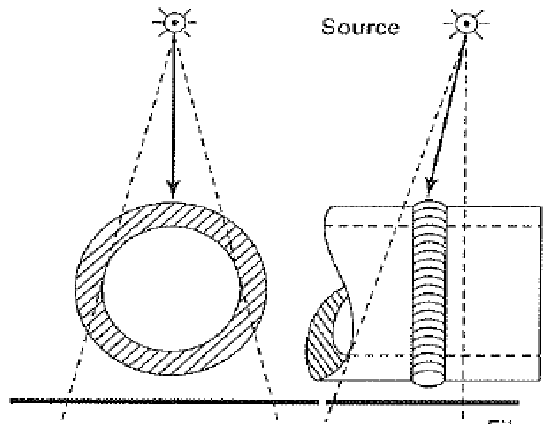
ASME Section V Requirements

FIG. A-210-1 SINGLE-WALL RADIOGRAPHIC TECHNIQUES

O.D.	Exposure Technique	Radiograph Viewing	Source-Weld-Film Arrangement		IQI		Location Marker Placement
			End View	Side View	Selection	Placement	
Any	Single-Wall T-271.1	Single-Wall	 Exposure Arrangement — A		T-276 and Table T-276	Source Side T-277.1(a) Film Side T-277.1(b)	Either Side T-275.3 T-275.1(c)
Any	Single-Wall T-271.1	Single-Wall	 Exposure Arrangement — C		T-276 and Table T-276	Source Side T-277.1(a) Film Side T-277.1(b)	Source Side T-275.1 (a)(3)

ASME Section V Requirements

FIG. A-210-2 DOUBLE-WALL RADIOGRAPHIC TECHNIQUES

O.D.	Exposure Technique	Radiograph Viewing	Source-Weld-Film Arrangement		IQI		Location Marker Placement
			End View	Side View	Selection	Placement	
Any	Double-Wall: T-271.2(a) at Least 3 Exposures 120 deg to Each Other for Complete Coverage	Single-Wall	 Exposure arrangement — D		T-276 and Table T-276	Source Side T-277.1(a) Film Side T-277.1(b)	Film Side T-275.1 (b)(1)
3½ in. (88 mm) or Less	Double-Wall T-271.2(b)(1) at Least 2 Exposures at 90 deg to Each Other for Complete Coverage	Double-Wall (Ellipse): Read Offset Source Side and Film Side Images	 Exposure arrangement — F		T-276 and Table T-276	Source Side T-277.1(a)	Either Side T-275.2

ASME Section V Requirements

- ASME Section V, Article 2, Radiographic Examination
  - T-280, Evaluation
    - Covers the evaluation requirements and describes ways to determine the quality of the radiograph
      - T-281, Quality of Radiographs
      - T-282, Radiographic Density
      - T-283, IQI Sensitivity
      - T-284, Excessive Backscatter
  - T-290, Documentation
    - Defines the minimum requirements for the examination record
      - Procedure used
      - Total number of radiographs
      - Equipment used including source size and film
      - Base material thickness, weld thickness, weld reinforcement thickness, etc.
      - Record of indications including location of markers
      - Type of exposure

ASME Section III – NB and B31.1 Acceptance Requirements for Radiographic Testing

- Section NB-5320 of ASME Section III provides radiographic examination acceptance criteria
- Section 136.4.5 of ASME B31.1 provides radiographic examination acceptance criteria
- Both standards references ASME Section V, Article 2

ASME Section III – NB and B31.1 Acceptance Requirements for Radiographic Testing

Criteria	ASME Section III – NB	ASME B31.1
Crack	Unacceptable	
Zone of Incomplete Fusion	Unacceptable	
Elongate Indication	¼ in. up to ¾ in. t (weld thickness)	
	1/3t for t from ¾ to 2 ¼ in.	
	¾ in. for t over 2 ¼ in.	
Internal Root Condition	Any abrupt change in density of image brightness	
	No elongated indications as defined above	
Aligned Indications	Aggregate length greater than t in a 12t length	
Round Indications	Any single indication greater than 1/4t or 5/32 in whichever is smaller	
	Any single indication greater than 1/3t or 1/4 in whichever is smaller for indications 1 in. or more apart	
	For t > 2 in. the maximum indication is 3/8”	

Advantages of Radiography

- Technique is not limited by material type or density
- Can inspect assembled components
- Minimum surface preparation required
- Sensitive to changes in thickness, corrosion, voids, cracks, and material density changes
- Detects both surface and subsurface defects
- Provides a permanent record of the inspection

Limitations of Radiography

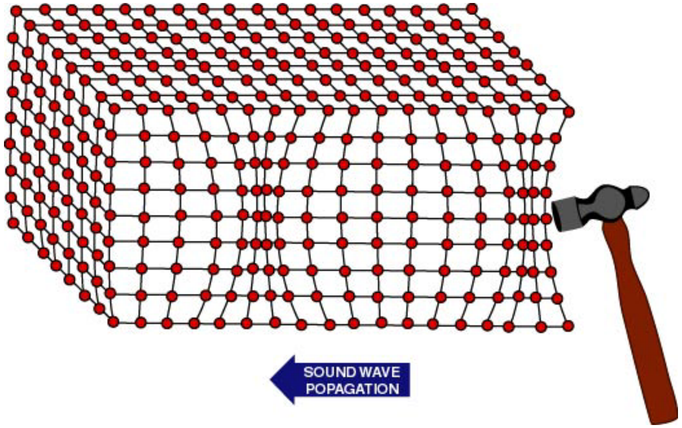
- Many safety precautions for the use of high intensity radiation
- Many hours of technician training prior to use
- Access to both sides of sample required
- Orientation of equipment and flaw can be critical
- Determining flaw depth is impossible without additional angled exposures
- Expensive initial equipment cost

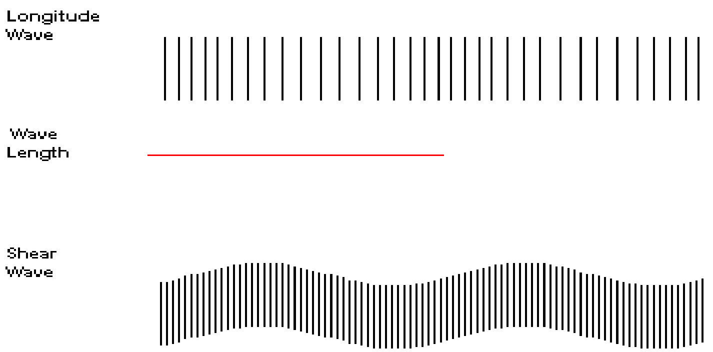
Ultrasonic Testing

Module 6A.6

Basic Principles of Sound

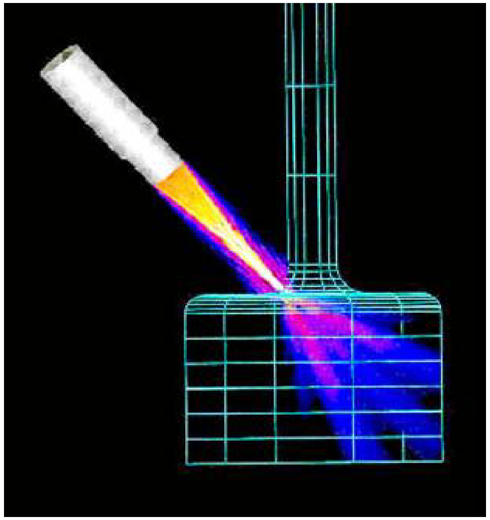
- Sound is produced by a vibrating body and travels in the form of a wave
  - Sound waves travel through materials by vibrating the particles that make up the material
  - The pitch of the sound is determined by the frequency of the wave (vibrations or cycles completed in a certain period of time)
  - Ultrasound is sound with a pitch too high to be detected by the human ear

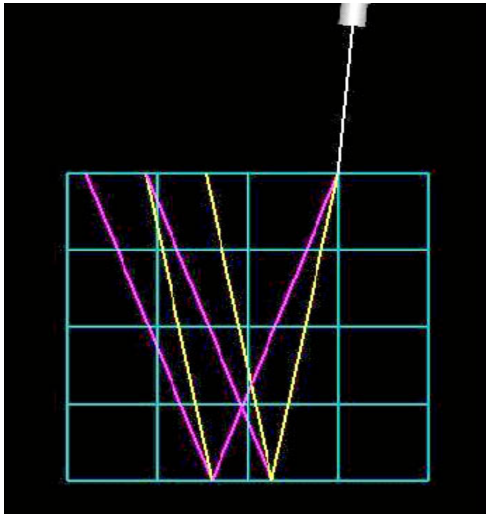




Basic Principles of Sound

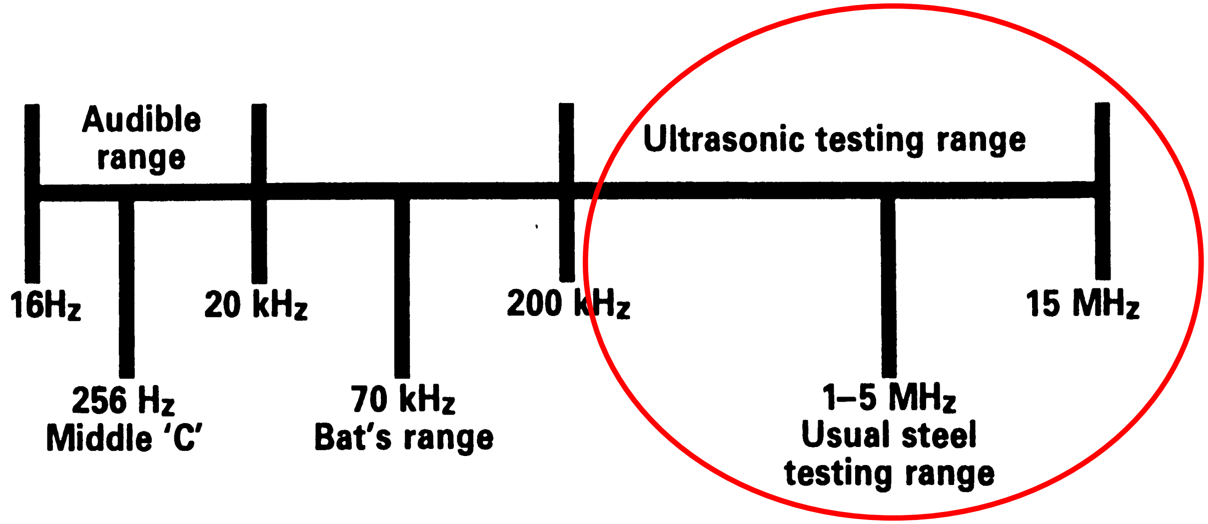
- Ultrasonic waves are very similar to light waves in that they can be reflected, refracted, and focused
- In solid materials, the vibrational energy can be split into different wave modes when the wave encounters an interface at an angle other than 90-degrees
- Ultrasonic reflections from the presence of discontinuities or geometric features enables detection and location
- The velocity of sound in a given material is constant and can only be altered by a change in the mode of energy





Frequency

- Since sound is a series of vibrations, one way of measuring it is to count the number of vibrations per second, which is frequency
- Unit of measurement is Hertz (Hz)
  - 1 Hz = 1 cycle/s
  - 1,000 Hz = 1 KHz = 1,000 cycles/s
  - 1,000,000 Hz = 1 MHz = 1,000,000 cycles/s



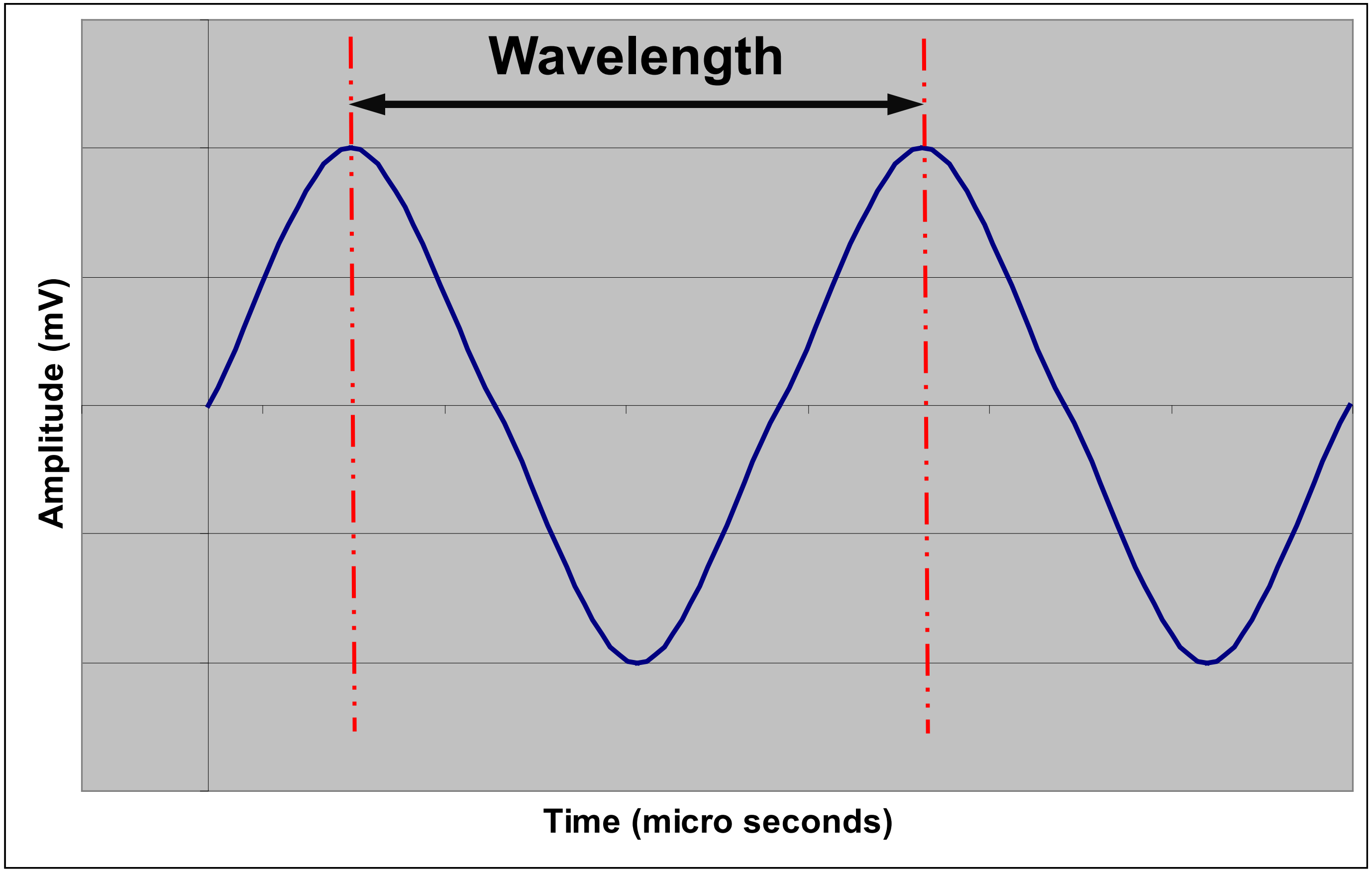
Typical Sound Velocities & Wavelengths

Material	LONGITUDINAL				SHEAR			
	Velocity		Wavelength @ 5 MHz		Velocity		Wavelength @ 5 MHz	
	M/s	in./µs	(mm)	(in.)	M/s	in./µs	(mm)	(in.)
Air	330	0.013	0.07	0.003	---	---	---	---
Aluminum	6300	0.248	1.26	0.050	3100	0.122	0.62	0.024
Copper	4660	0.183	0.93	0.037	2260	0.089	0.45	0.018
Plexiglass	2700	0.106	0.54	0.021	1100	0.043	0.22	0.009
Rexolite	2330	0.092	0.47	0.018	1100	0.043	0.22	0.009
Carbon Steel	5900	0.232	1.18	0.046	3230	0.127	0.65	0.025
Titanium	6100	0.240	1.22	0.048	3100	0.122	0.62	0.024
Water	1480	0.058	0.30	0.012	---	---	---	---

Wavelength

- Wavelength is the distance from one point to the next identical point along a repetitive waveform
- It is dependent upon the material sound velocity and the transducer frequency
- Wavelength (λ) = Velocity/Frequency or $\lambda = \frac{V}{F}$
- Typical wavelength
  - Wavelength of 200 Hz sound in air = 332/200 = 1.66 m
  - Wavelength of 2 MHz compression wave in steel = 5,920/2,000,000 = 2.96 mm
  - Wavelength of 2 MHz shear wave in steel = 3,250/2,000,000 = 1.63 mm

Wavelength

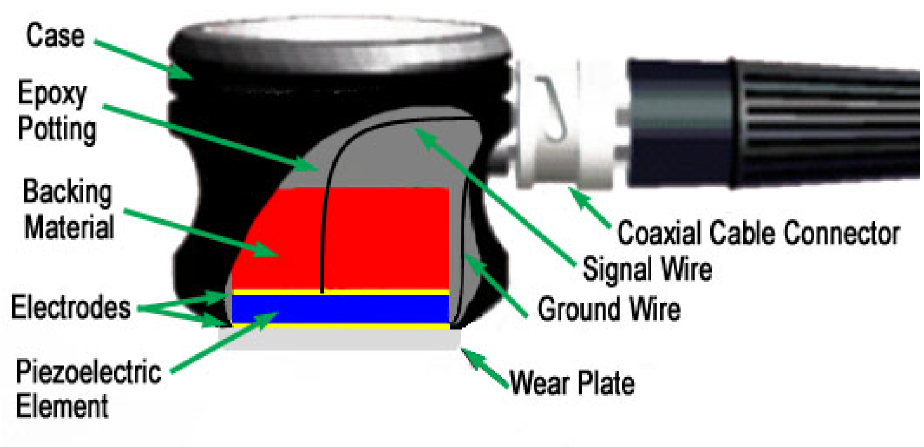


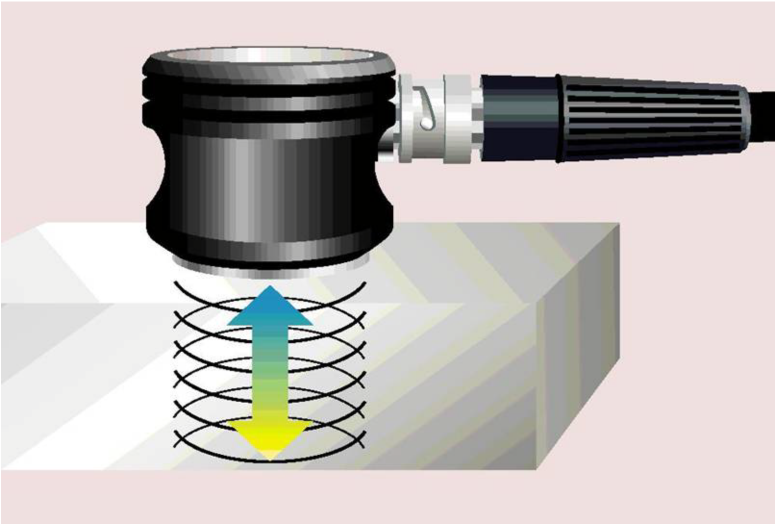
Effects of Wavelength in UT

- Shorter wavelengths can detect smaller flaws
  - Therefore, shear waves of a given frequency will be capable of detecting smaller flaws in a material than compression waves
- Discontinuities of a size less than $\lambda/2$ may not be detected
- Shorter wavelengths attenuate quicker and therefore do not penetrate thicker material as well as long wavelengths would

Ultrasound Generation

- Ultrasound is generated with a transducer
  - A piezoelectric element in the transducer converts electrical energy into mechanical vibrations (sound), and vice versa



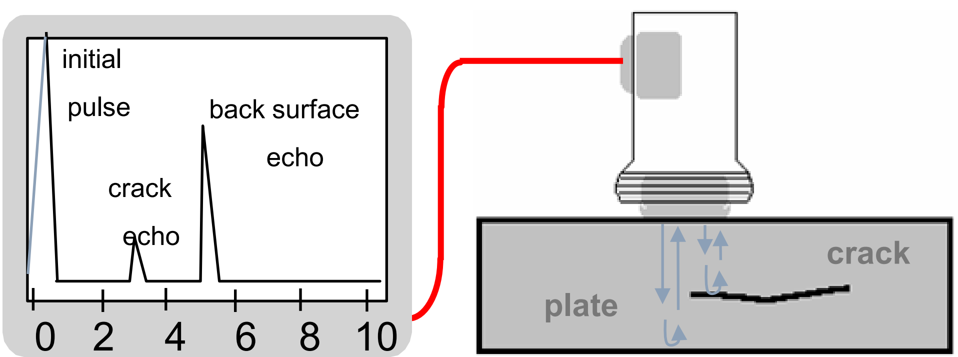


Principles of Ultrasonic Inspection

- Ultrasonic waves are introduced into a material where they travel in a straight line and at a constant speed until they encounter a surface.
- At surface interfaces some of the wave energy is reflected and some is transmitted.
- The amount of reflected or transmitted energy can be detected and provides information about the size of the reflector.
- The travel time of the sound can be measured and this provides information on the distance that the sound has traveled.

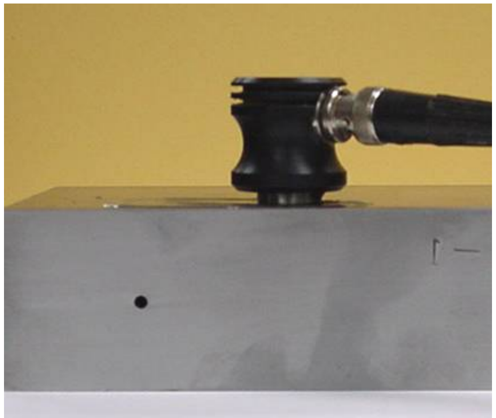
Test Techniques – Pulse-Echo

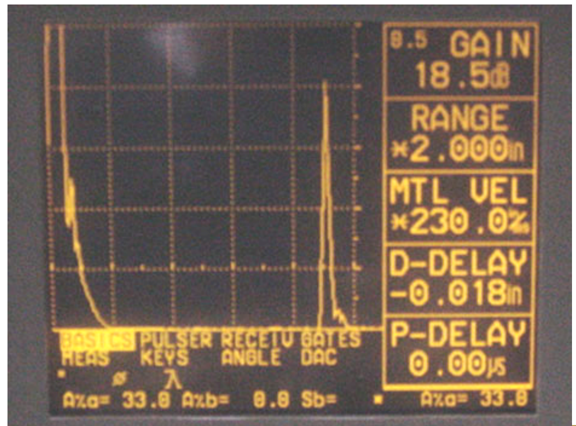
- In pulse-echo testing, a transducer sends out a pulse of energy and the same or a second transducer listens for reflected energy (an echo)
- Reflections occur due to the presence of discontinuities and the surfaces of the test article
- The amount of reflected sound energy is displayed versus time, which provides the inspector information about the size and the location of features that reflect the sound



UT Instrument Screen

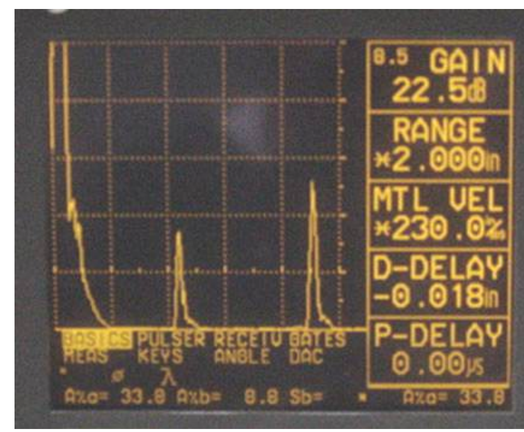
Test Techniques – Pulse-Echo





Digital display showing signal generated from sound reflecting off back surface

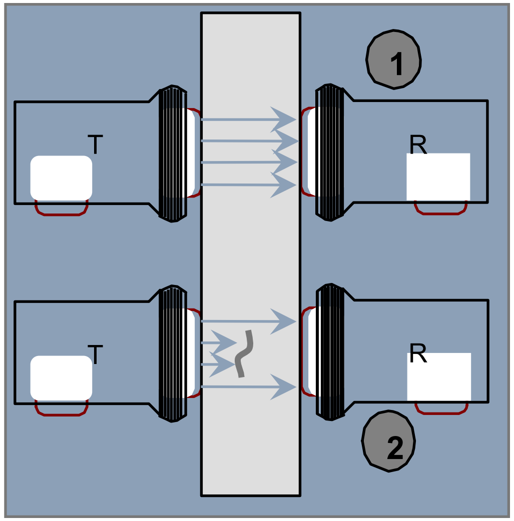
Digital display showing the presence of a reflector midway through material, with lower amplitude back surface reflector

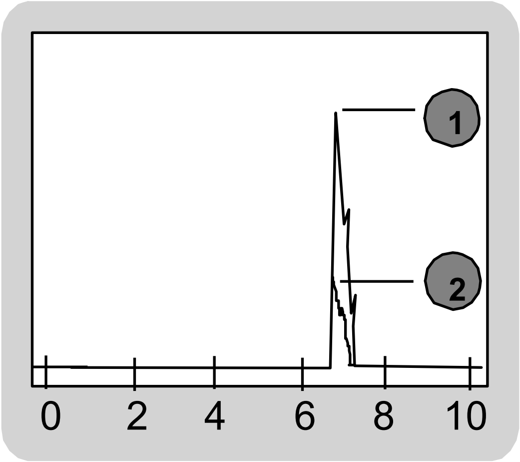


The pulse-echo technique allows testing when access to only one side of the material is possible, and it allows the location of reflectors to be precisely determined

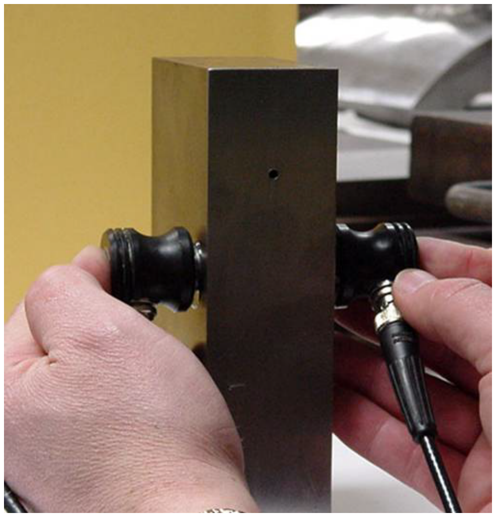
Test Techniques – Through Transmission

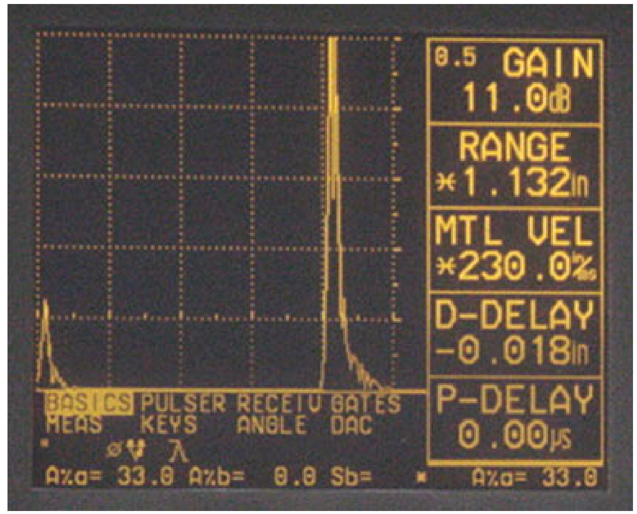
- Two transducers located on opposing sides of the test specimen are used.
  - One transducer acts as a transmitter, the other as a receiver
- Discontinuities in the sound path will result in a partial or total loss of sound being transmitted and be indicated by a decrease in the received signal amplitude
- Through transmission is useful in detecting discontinuities that are not good reflectors, and when signal strength is weak
- It does not provide depth information



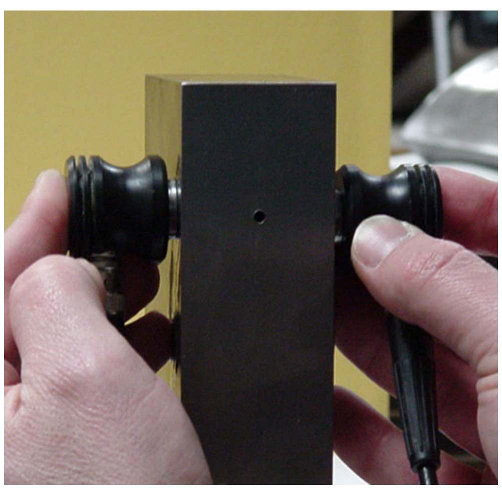


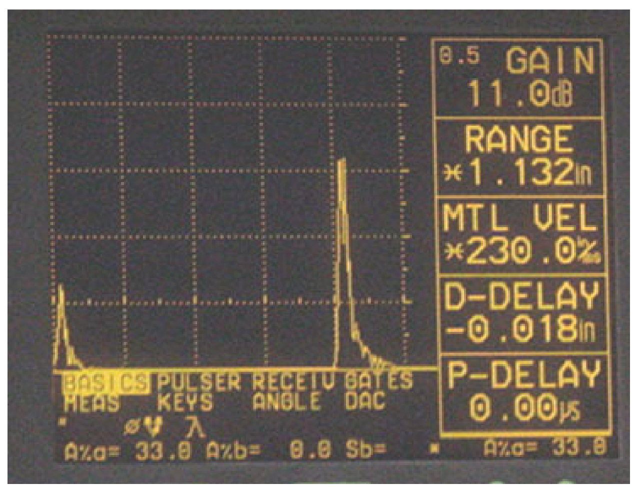
Test Techniques – Through Transmission





Digital display showing received sound through material thickness

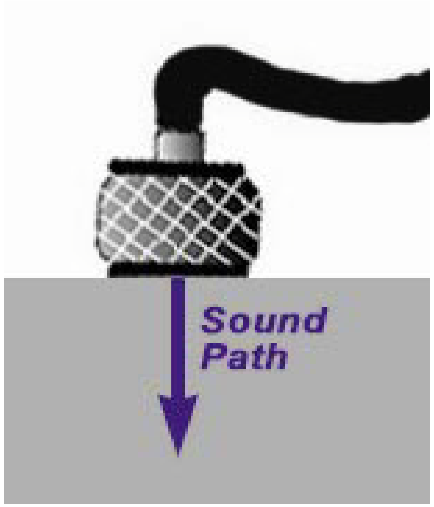


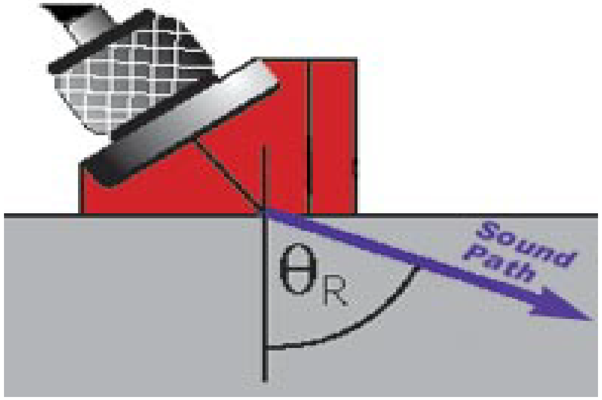


Digital display showing loss of received signal due to presence of a discontinuity in the sound field

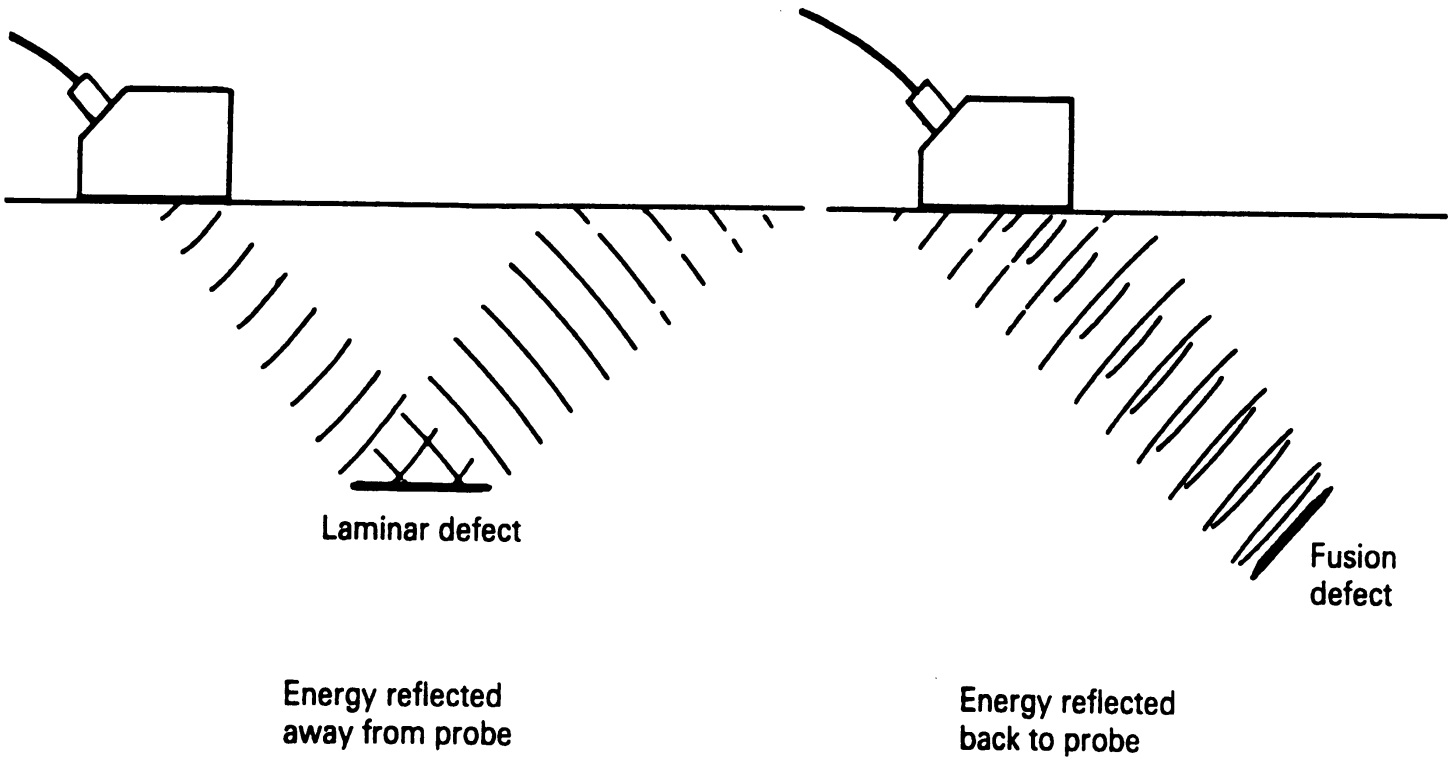
Test Techniques – Normal and Angle Beam

- In normal beam testing, the sound beam is introduced into the test article at 90º to the surface
- In angle beam testing, the sound beam is introduced into the test article at some angle other than 90º
- The choice between normal and angle beam inspection usually depends on:
  - The orientation of the feature of interest
  - Obstructions on the surface of the part that must be worked around

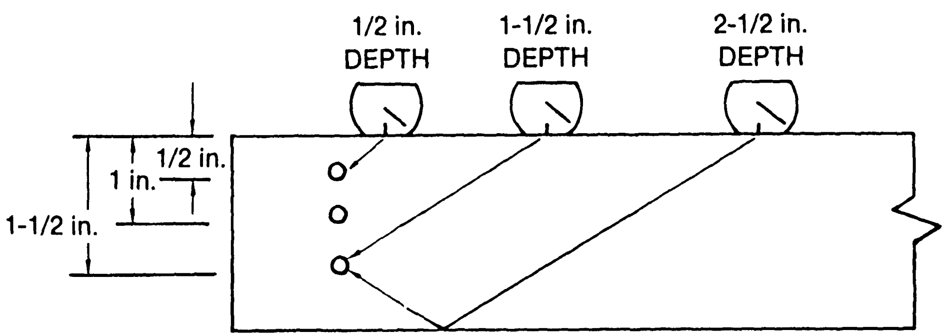


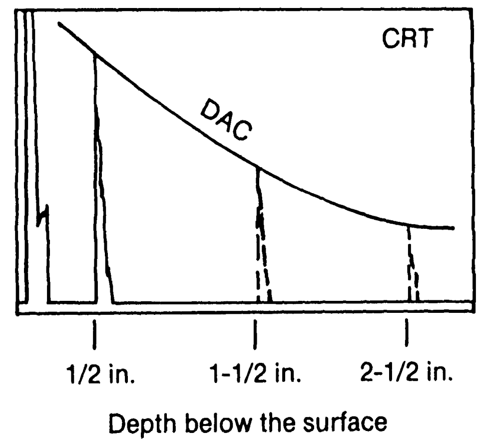


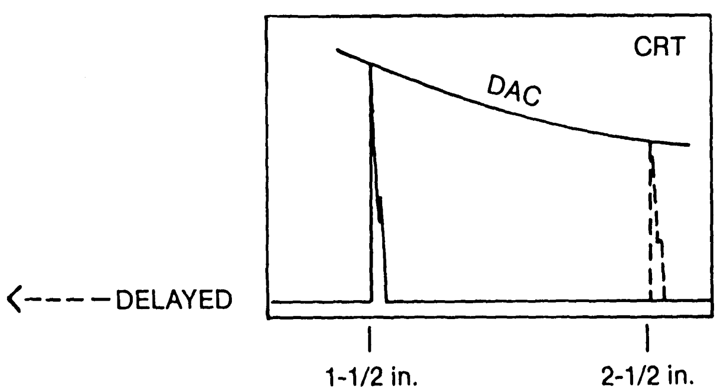
Effect of Flaw Orientation and Beam Angle



Distance Amplitude Correction (DAC)



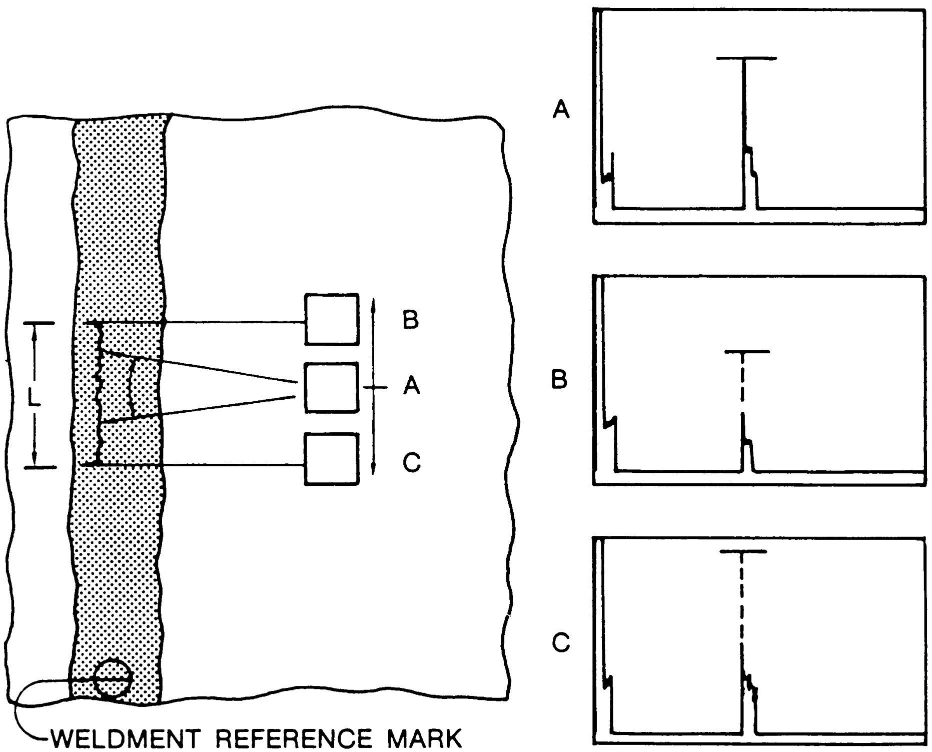




Example: Delayed technique for discontinuities between 1-1/2 in. - 2-1/2 in. for greater accuracy of determining depth location and height measurement.

Sizing Weld Discontinuities

- Determining Weld Discontinuity Length Dimension



Determine discontinuity orientation and minimum/maximum indication height.

Move search unit to end B until indication drops to 1/2 of height near the end. Mark scanning surface adjacent to search unit reference center beam reference mark.

Move search unit to end C and repeat B, above. Indication length (L) is the distance between both marks.

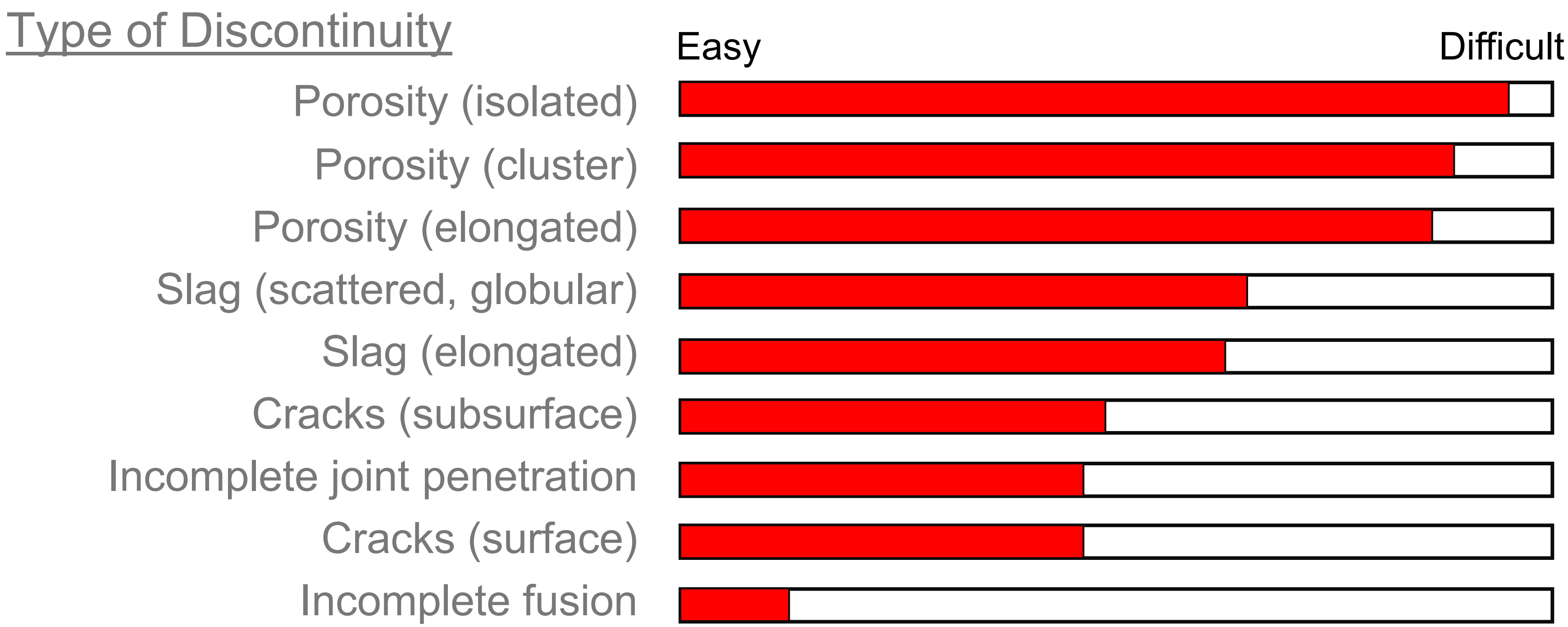
L = Total length of discontinuity

Discontinuity location along the weld is from the weldment reference mark.

Inspection Applications

- There are numerous applications for which UT may be employed
  - Flaw detection (cracks, inclusions, porosity, etc.)
  - Erosion & corrosion thickness gauging
  - Assessment of bond integrity in adhesively joined and brazed components
  - Estimation of void content in composites and plastics
  - Measurement of case hardening depth in steels
  - Estimation of grain size in metals

Relative Difficulty of Discontinuity Detection Using UT

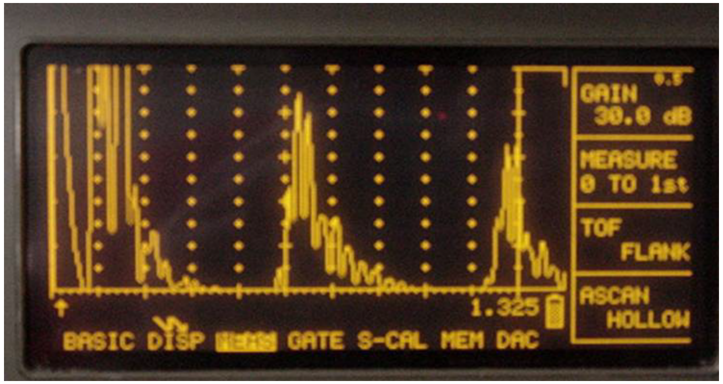


Thickness Gauging

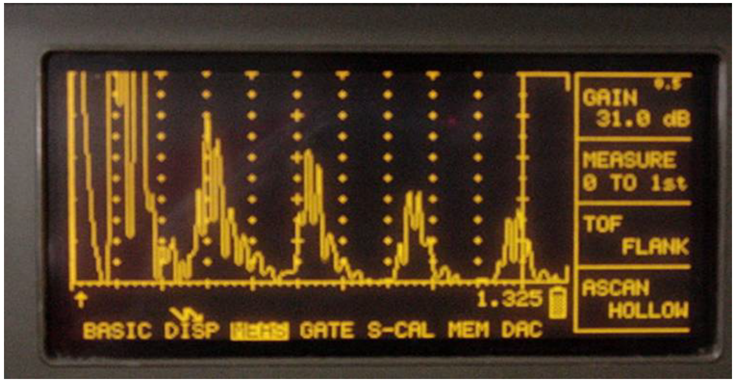
- Ultrasonic thickness gauging is routinely utilized in the petrochemical and utility industries to determine various degrees of corrosion/erosion
- Applications include piping systems, storage and containment facilities, and pressure vessels

Flaw Detection - Delaminations

Contact, pulse-echo inspection for delaminations on 36" rolled beam



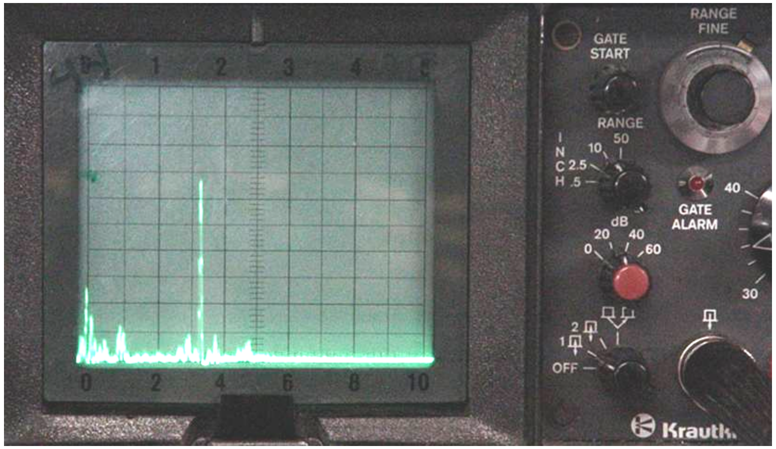
Signal showing multiple back surface echoes in an unflawed area

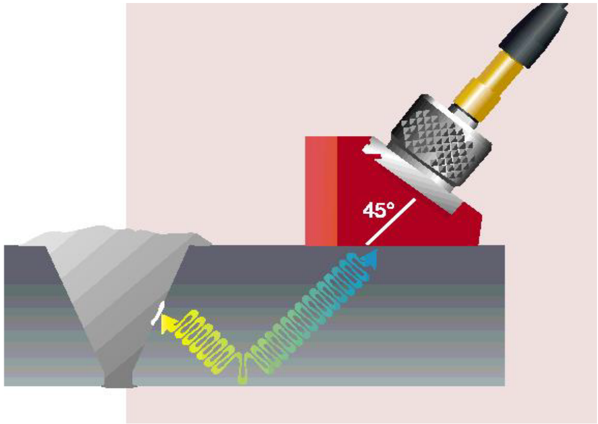


Additional echoes indicate delaminations in the member

Flaw Detection in Welds

- One of the most widely used methods of inspecting weldments is ultrasonic inspection
- Full penetration groove welds lend themselves readily to angle beam shear wave examination





Equipment

- Equipment for ultrasonic testing is very diversified and proper selection is important to insure accurate inspection data as desired for specific applications
- UT systems are generally comprised of three basic components
    - Instrumentation
    - Transducers
    - Calibration Standards

Transducers

- Transducers are manufactured in a variety of forms, shapes, and sizes for varying applications
- Transducers are categorized in a number of ways which include:
  - Contact or immersion
  - Single or dual element
  - Normal or angle beam

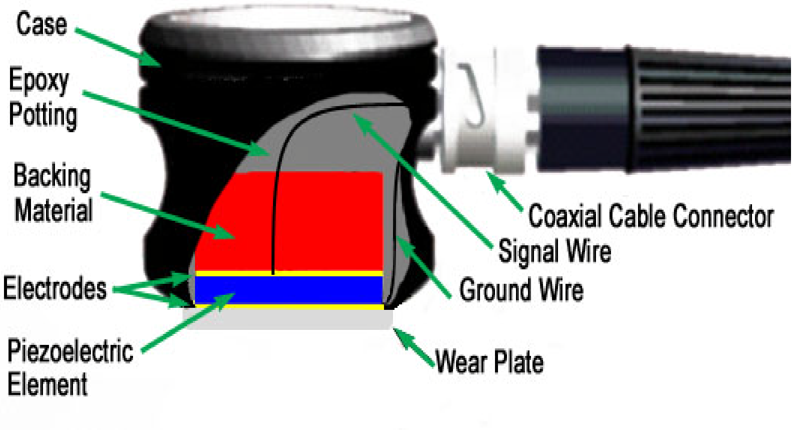
- In selecting a transducer, it is important to choose the desired frequency, bandwidth, size, and in some cases focusing, which optimizes the inspection capabilities

Probe Selection

- Factors to be considered:
  - Test object thickness
  - Test object diameter
  - Surface condition
  - Metallurgical condition, e.g., grain size
  - Type, position, and orientation of likely discontinuities
  - Flaw sizing accuracy (beam should be smaller than flaw)

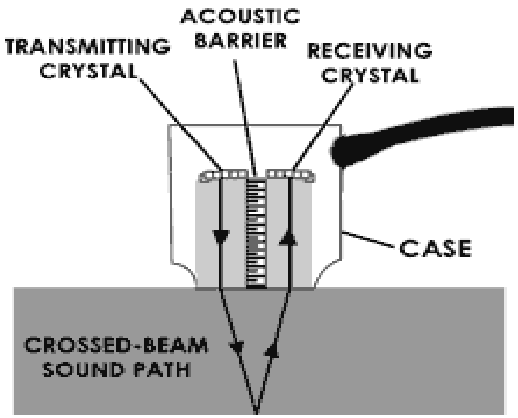
Contact Transducers

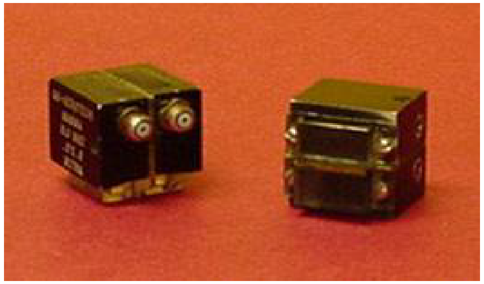
- Contact transducers are designed to withstand rigorous use and usually have a wear plate on the bottom surface to protect the piezoelectric element from contact with the surface of the test article
- Many incorporate ergonomic designs for ease of grip while scanning along the surface



Contact Transducers

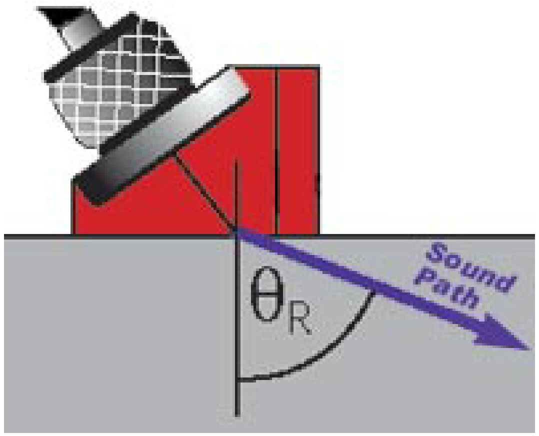
- Contact transducers with two piezoelectric crystals in one housing are called dual element transducers
  - One crystal acts as a transmitter, the other as a receiver
  - This arrangement improves near surface resolution because the second transducer does not need to complete a transmit function before listening for echoes
  - Dual elements are commonly employed in thickness gauging of thin materials

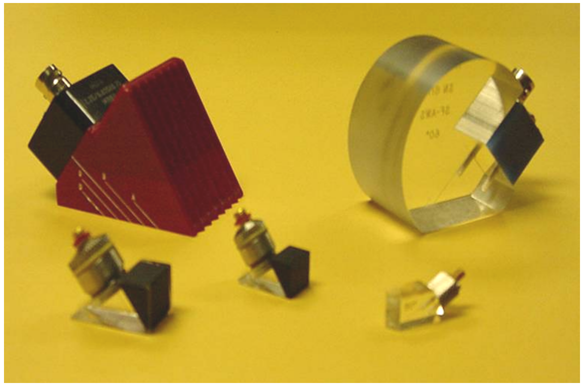




Angle Beam Transducers

- Angle beam transducers incorporate wedges to introduce a refracted shear wave into a material
- The incident wedge angle is used with the material velocity to determine the desired refracted shear wave according to Snell's Law
- Transducers can use fixed or variable wedge angles
- Common application is in weld examination

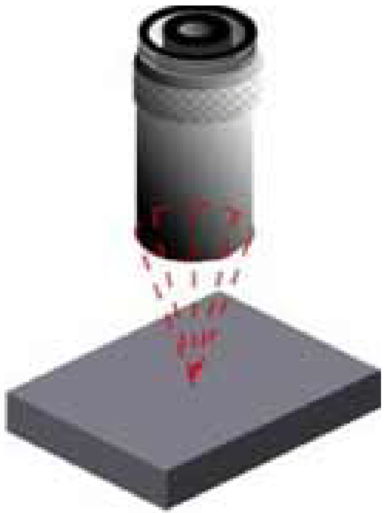




Immersion Transducers

- Immersion transducers are designed to transmit sound whereby the transducer and test specimen are immersed in a liquid coupling medium (usually water)
- Immersion transducers are manufactured with planar, cylindrical or spherical acoustic lenses (focusing lens)

Cylindrical Focus



Spherical Focus

Instrumentation

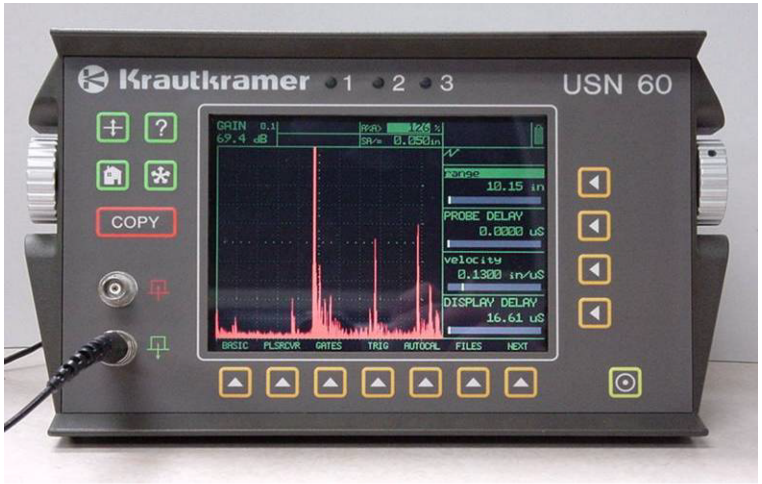
- Ultrasonic equipment is usually purchased to satisfy specific inspection needs
  - Some users may purchase general purpose equipment to fulfill a number of inspection applications
- Test equipment can be classified in a number of different ways
  - Portable or stationary
  - Contact or immersion
  - Manual or automated
- Further classification of instruments commonly divides them into four general categories
  - D-meters
  - Flaw detectors
  - Industrial
  - Special application

Instrumentation D-Meters

- D-meters or digital thickness gauge instruments provide the user with a digital readout
- They are designed primarily for corrosion/ erosion inspection applications
- Some instruments provide the user with both a digital readout and a display of the signal
  - A distinct advantage of these units is that they allow the user to evaluate the signal to ensure that the digital measurements are of the desired features

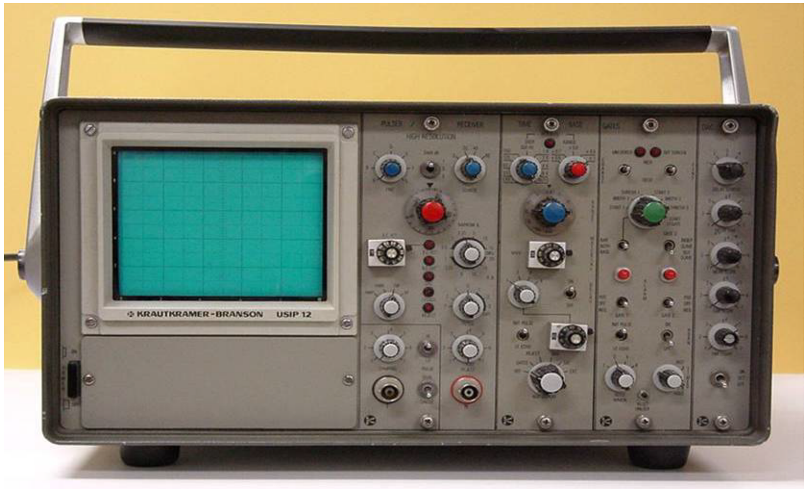
Instrumentation Flaw Detectors

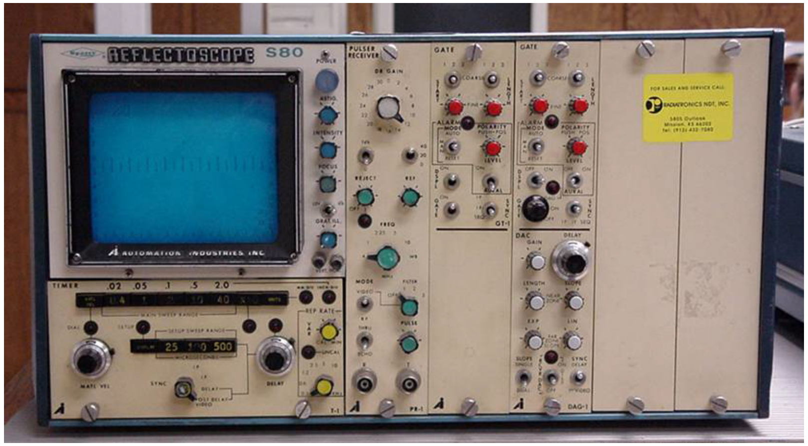
- Flaw detectors are instruments designed primarily for the inspection of components for defects
- However, the signal can be evaluated to obtain other information such as material thickness values
- Both analog and digital display
- Offer the user options of gating horizontal sweep and amplitude threshold



Instrumentation Flaw Detectors

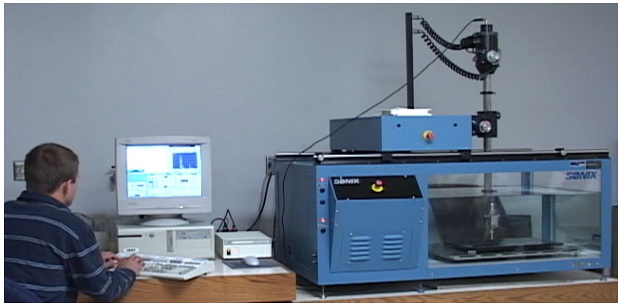
- Industrial flaw detection instruments provide users with more options than standard flaw detectors
- May be modulated units allowing users to tailor the instrument for their specific needs
- Generally not as portable as standard flaw detectors

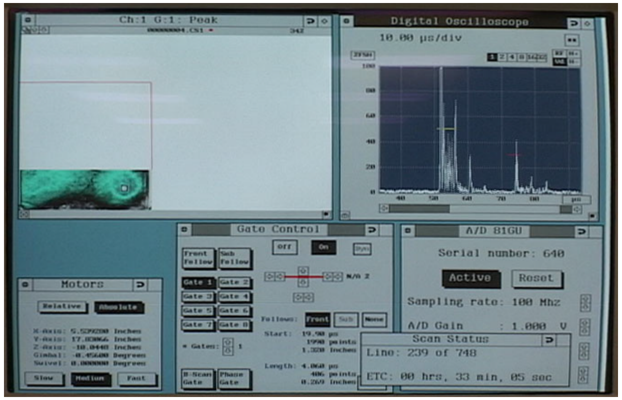




Instrumentation Immersion System

- Immersion ultrasonic scanning systems are used for automated data acquisition and imaging
  - They integrate an immersion tank, ultrasonic instrumentation, a scanning bridge, and computer controls
  - The signal strength and/or the time-of-flight of the signal is measured for every point in the scan plan
  - The value of the data is plotted using colors or shades of gray to produce detailed images of the surface or internal features of a component



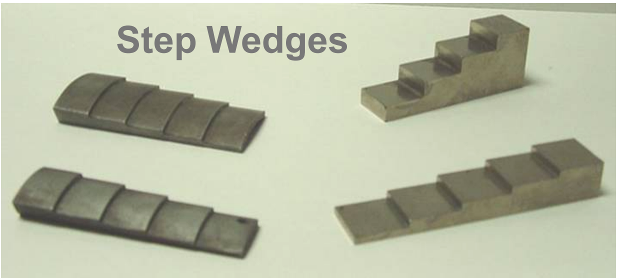


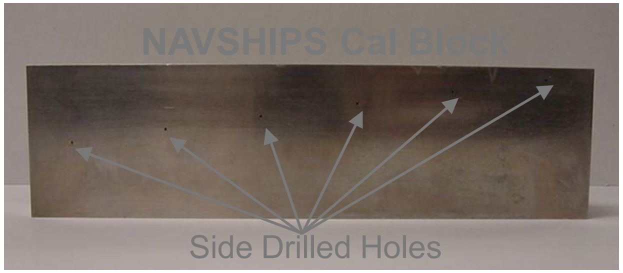
Calibration Standards

- Calibration is a operation of configuring the ultrasonic test equipment to known values
- Calibration provides the inspector with a means of comparing test signals to known measurements
- Calibration standards come in a wide variety of material types, and configurations due to the diversity of inspection applications
- Calibration standards are typically manufactured from materials of the same acoustic properties as those of the test articles

Calibration Standards

- Thickness calibration standards may be flat or curved for pipe and tube applications, consisting of simple variations in material thickness
- Distance/Area Amplitude standards utilize flat bottom holes (FBH) or side drilled holes (SDH) to establish a known reflector size with changes in sound path from the entry surface



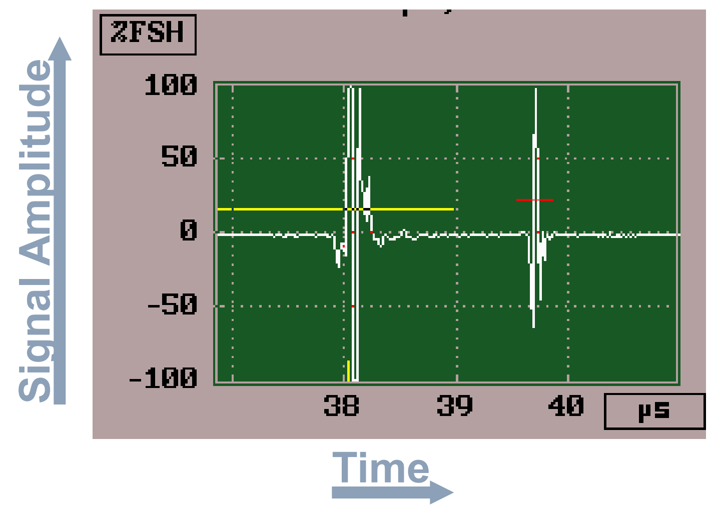


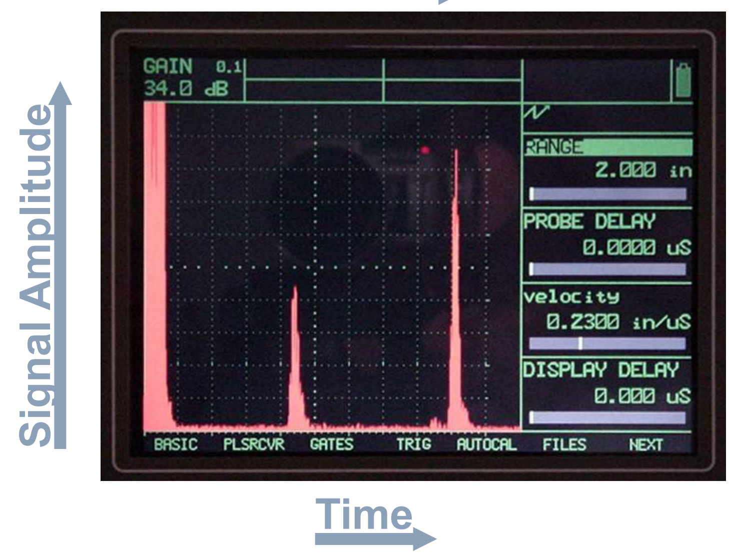
Data Presentation

- Information from ultrasonic testing can be presented in a number of differing formats
- Three of the more common formats include:
  - A-scan
  - B-scan
  - C-scan

Data Presentation – A-Scan

- A-scan presentation displays the amount of received ultrasonic energy as a function of time
- Relative discontinuity size can be estimated by comparing the signal amplitude to that from a known reflector
- Reflector depth can be determined by the position of the signal on the horizontal sweep



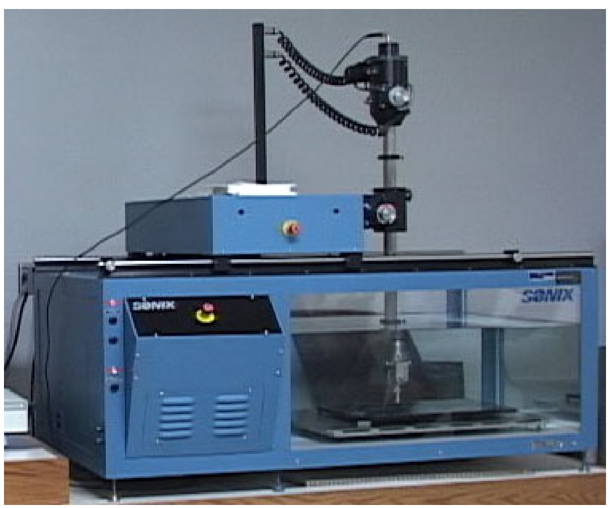


Data Presentation – B-scan

- B-scan presentations display a profile view (cross-sectional) of a test specimen
- Only the reflector depth in the cross-section and the linear dimensions can be determined
- A limitation to this display technique is that reflectors may be masked by larger reflectors near the surface

Data Presentation – C-Scan

- The C-scan presentation displays a plan type view of the test specimen and discontinuities
  - C-scan presentations are produced with an automated data acquisition system, such as in immersion scanning
  - Use of A-scan in conjunction with C-scan is necessary when depth determination is desired



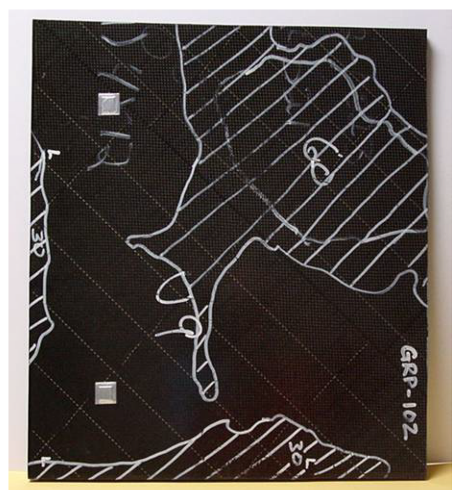
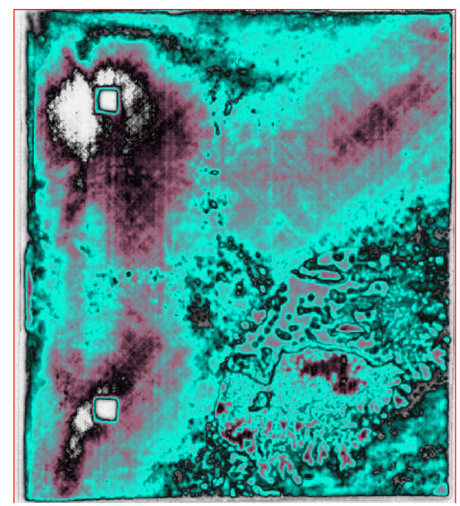


Photo of a Composite Component



C-Scan Image of Internal Features

ASME Section V Requirements

- ASME Section V, Article 4, Ultrasonic Examination Methods for Welds
  - The section refers to different mandatory appendices depending on equipment and technique applied
    - Appendix I, Screen Height Linearity
    - Appendix II, Amplitude Control Linearity
    - Appendix III, Time of Flight Diffraction (TOFD) Technique
    - Appendix IV, Phased Array Manual Raster Examination Techniques Using Linear Arrays
  - There is a nonmandatory appendix the provides recommendations for calibration including calibration blocks, recording data and interpretation

ASME Section V Requirements

- ASME Section V, Article 4, Ultrasonic Examination Methods for Welds
  - T-420, General Requirements
    - Lists the requirements for written procedures and procedure qualifications T-430, Equipment
    - Describes different types of equipment
      - T-433, Couplant
      - T-434 Calibration Blocks
  - T-440, Miscellaneous Requirements
    - Defines how to identify the weld locations, how to mark the welds and generate a reference point
  - T-450, Techniques
    - Describes different types of examination techniques and defines the terms “straight beam” and “angle beam”
  - T-460, Calibration
    - Lists the calibration requirements and the equipment linearity checks that need to be performed

ASME Section V Requirements

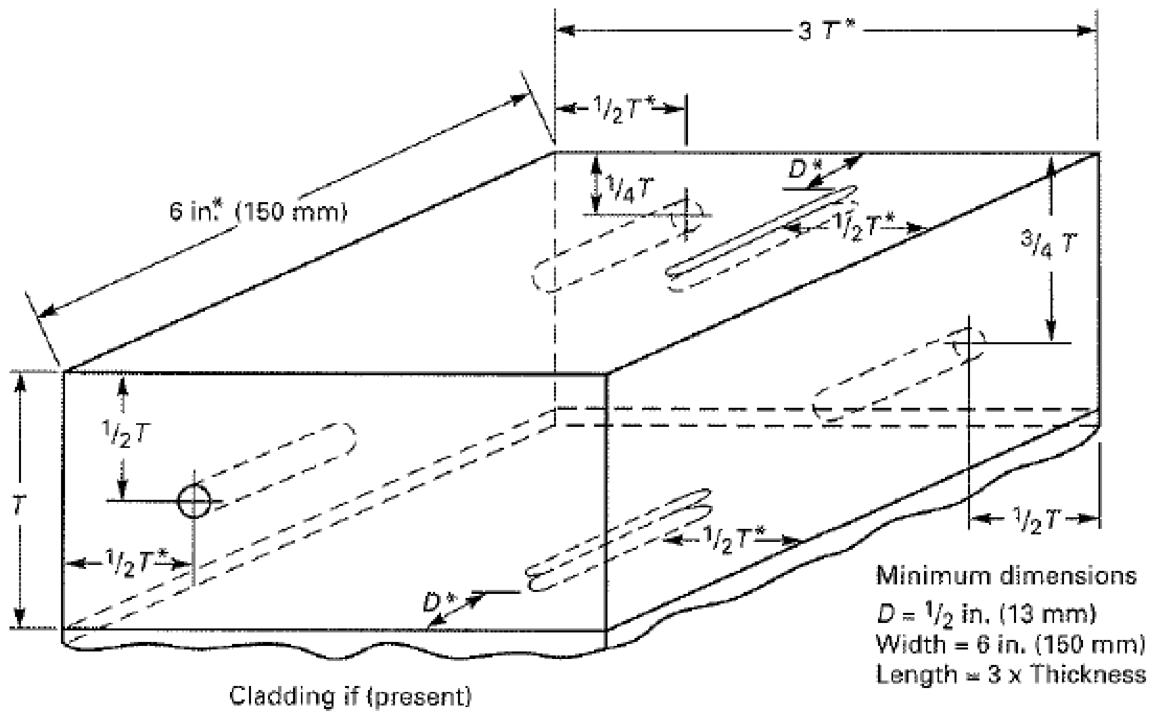
Requirement (as applicable)	Essential Variable	Nonessential Variable
Weld configuration to be examined, including thickness dimensions and base material product form (pipe, plate, etc.)	X	
The surfaces from which the examination shall be performed	X	
Technique(s) (straight beam, angle beam, contact, and/or immersion)	X	
Angle(s) and mode(s) of wave propagation in the material	X	
Search unit type(s), frequency(ies), and element size(s)/shape(s)	X	
Special search units, wedges, shoes, or saddles, when used	X	
Ultrasonic instrument(s)	X	
Calibration [calibration block(s) and technique(s)]	X	
Direction and extent of scanning	X	
Scanning (manual vs. automatic)	X	

ASME Section V Requirements

Requirement (as applicable)	Essential Variable	Nonessential Variable
Method for discriminating geometric from flaw indications	X	
Method for sizing indications	X	
Computer enhanced data acquisition, when used	X	
Scan overlap (decrease only)	X	
Personnel performance requirements, when required	X	
Personnel qualification requirements		X
Surface condition (examination surface, calibration blocks)		X
Couplant: brand name or type		X
Automatic alarm and/or recording equipment, when applicable		X
Records, including minimum calibration data to be recorded (e.g., instrument settings)		X

ASME Section V Requirements

FIG. T-434.2.1 NON-PIPING CALIBRATION BLOCKS

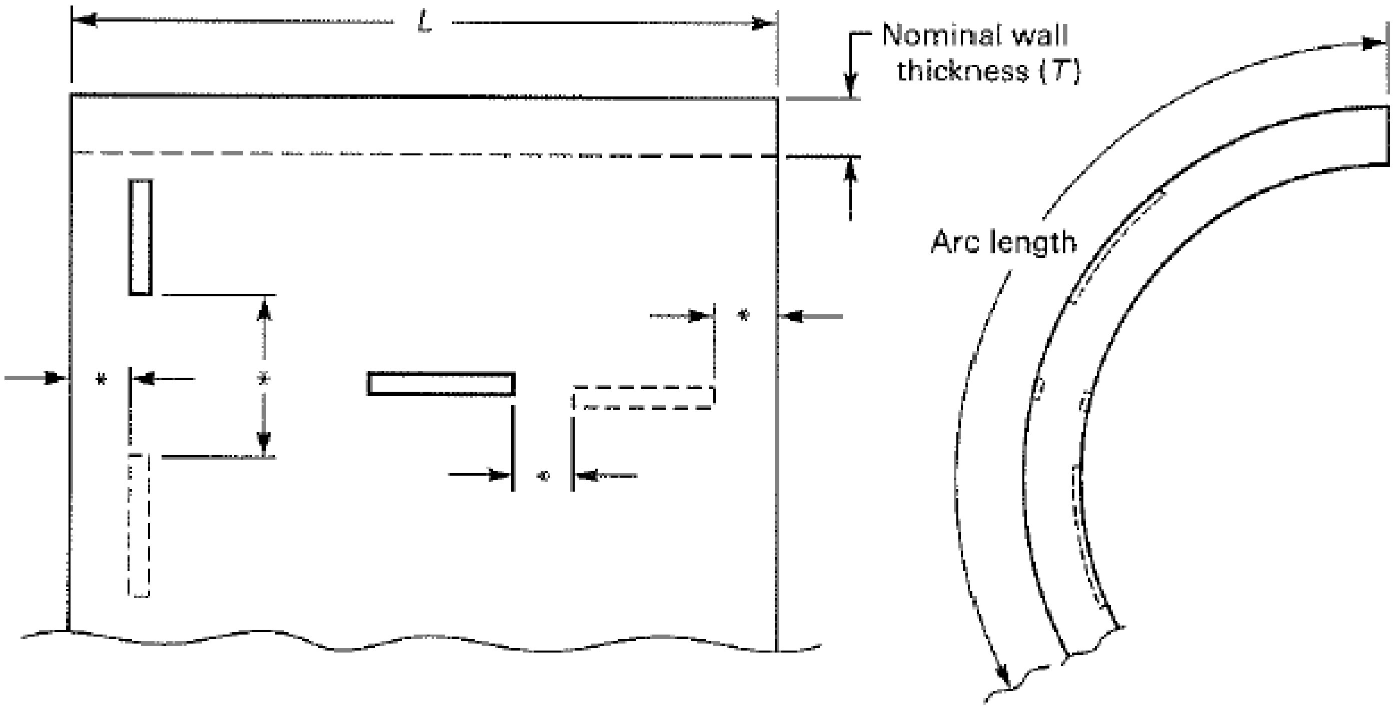


Weld Thickness (t), in. (mm)	Calibration Block Thickness (T), in. (mm)	Hole Diameter, in. (mm)
Up to 1 (25)	¾ (19) or t	$\frac{3}{32}$ (2.5)
Over 1 (25) through 2 (50)	1½ (38) or t	⅛ (3)
Over 2 (50) through 4 (100)	3 (75) or t	$\frac{3}{16}$ (5)
Over 4 (100)	$t \pm 1$ (25)	[Note (1)]

Notch Dimensions, in. (mm)
Notch depth = 2% T
Notch width = ¼ (6) max.
Notch length = 1 (25) min.

ASME Section V Requirements

FIG. T-434.3 CALIBRATION BLOCK FOR PIPE



* Notches shall be located not closer than T or 1 in. (25 mm), whichever is greater, to any block edge or to other notches.

ASME Section V Requirements

- ASME Section V, Article 4, Ultrasonic Examination Methods for Welds
  - T-470, Examination
    - Covers the different technique and requirements for examination
      - T-471, General Examination Requirements
      - T-472, Weld Joint Distance Amplitude Technique
      - T-473, Cladding Technique
      - T-274, Non-Distance Amplitude Technique
  - T-480, Evaluation
    - Covers the evaluation requirements and describes techniques used to evaluate the reflectors

ASME Section V Requirements

- ASME Section V, Article 4, Ultrasonic Examination Methods for Welds
  - T-490, Documentation
    - Defines what are considered non-rejectable and rejectable indications
      - Refers to the code of construction
    - Specifies the minimum requirements for the examination record
      - Procedure used including beam angles
      - Equipment used any special equipment
      - Calibration block used
      - Map or record of rejectable indications
      - Examination personnel
      - Date of examination

ASME Section III – NB and B31.1 Acceptance Requirements for Ultrasonic Testing

- Section NB-5330 of ASME Section III provides ultrasonic examination acceptance criteria
- Section 136.4.6 of ASME B31.1 provides ultrasonic examination acceptance criteria
- Both standards references ASME Section V, Article 4

ASME Section III – NB and B31.1 Acceptance Requirements for Radiographic Testing

Criteria	ASME Section III – NB	ASME B31.1
Crack	Unacceptable	
Lack of Fusion	Unacceptable	
Incomplete Penetration	Unacceptable	
	Indication greater than 20 % and length ≥ ¼ in. up to ¾ in. t (weld thickness)	
	Indication greater than 20 % and length ≥ 1/3t for t from ¾ to 2 ¼ in.	
Indication	Indication greater than 20 % and length ≥ ¾ in. for t over 2 ¼ in.	

Advantage of Ultrasonic Testing

- Sensitive to both surface and subsurface discontinuities
- Depth of penetration for flaw detection or measurement is superior to other methods
- Only single-sided access is needed when pulse-echo technique is used
- High accuracy in determining reflector position and estimating size and shape
- Minimal part preparation required
- Electronic equipment provides instantaneous results
- Detailed images can be produced with automated systems
- Has other uses such as thickness measurements, in addition to flaw detection

Limitations of Ultrasonic Testing

- Surface must be accessible to transmit ultrasound
- Skill and training is more extensive than with some other methods
- Normally requires a coupling medium to promote transfer of sound energy into 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 characterization of flaws

NDE Advancements

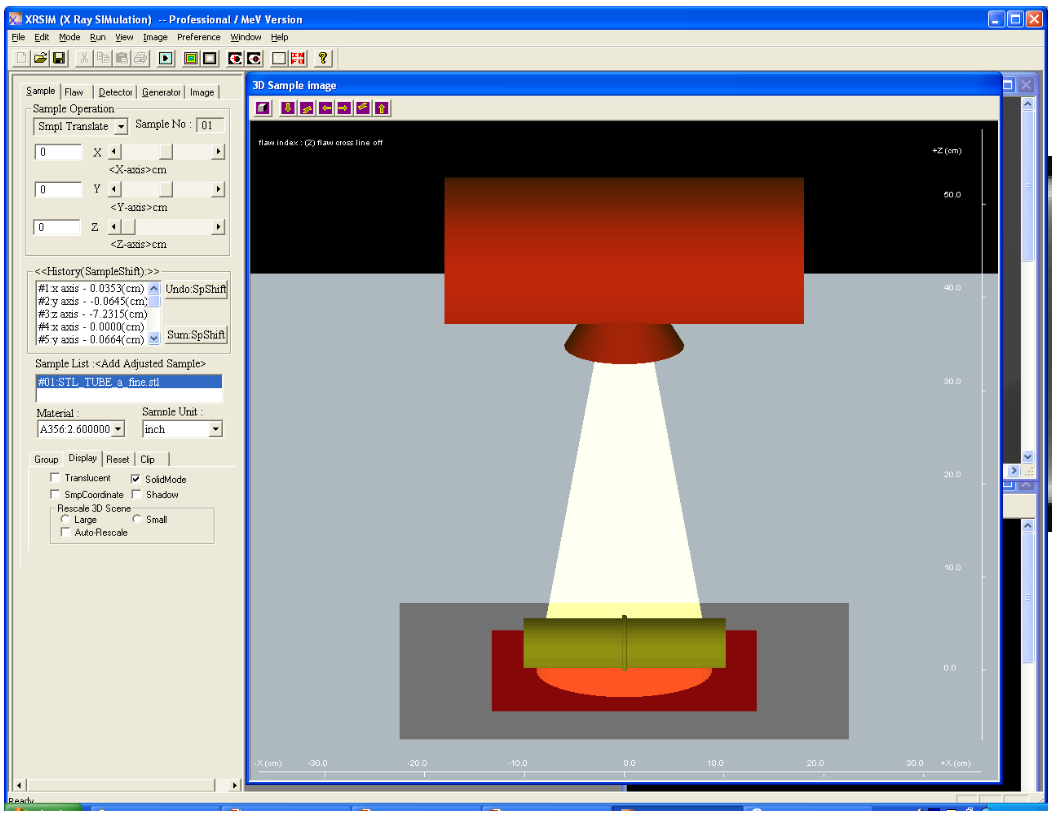
Module 6B

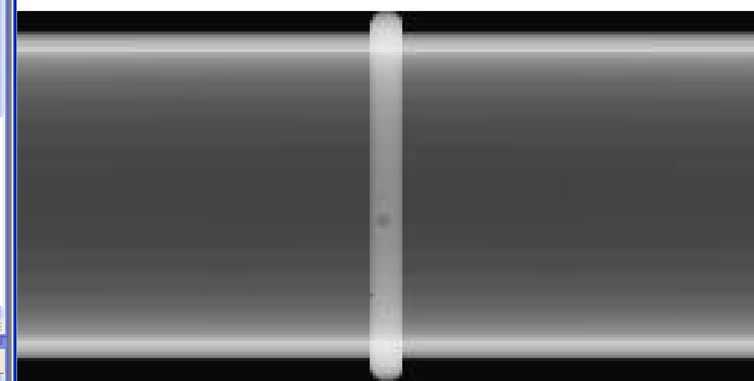
NDE Modeling

- Modeling and simulation offers significant flexibility and cost reduction during the development and implementation of NDT process
  - Modeling of radiography
  - Modeling conventional and phased array UT
  - Modeling of eddy current

RT Modeling

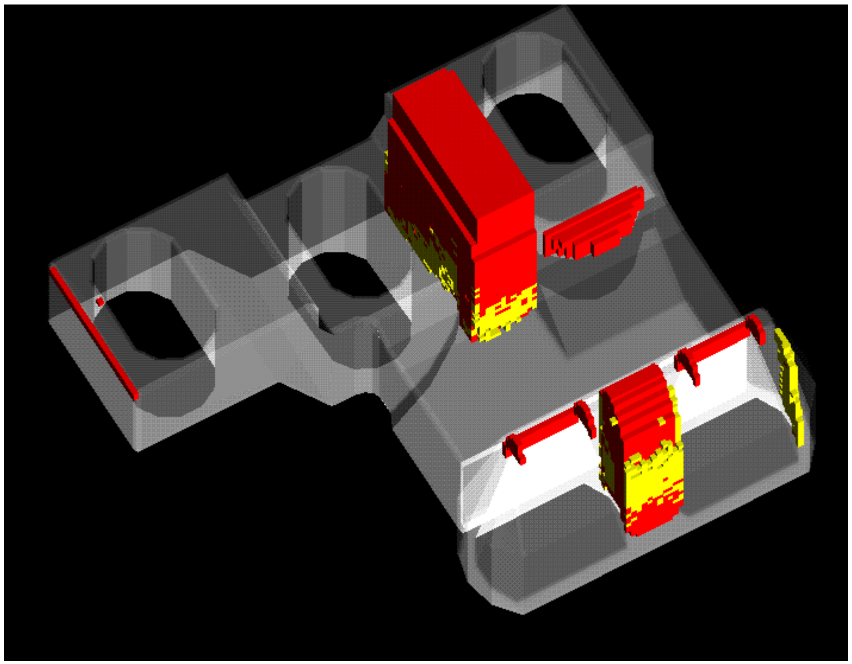
- Simulated X-Ray Radiograph of Weld Butt Joint with Weld Defects



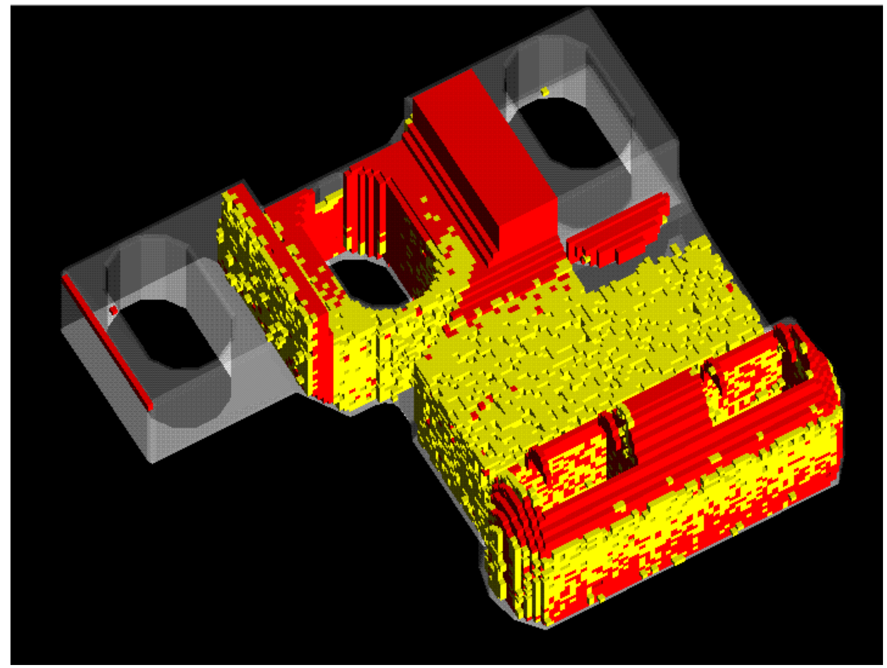


Setup Screen

RT Modeling - 3D POD Maps



0.6-mm Flaw



0.4-mm Flaw

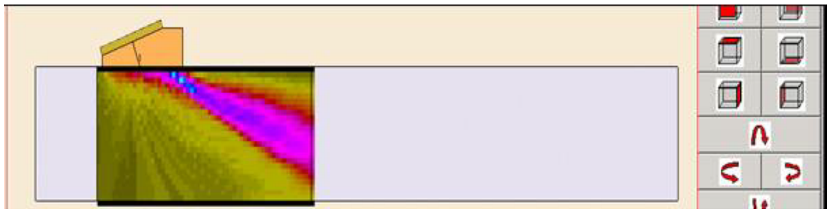
Undetectable

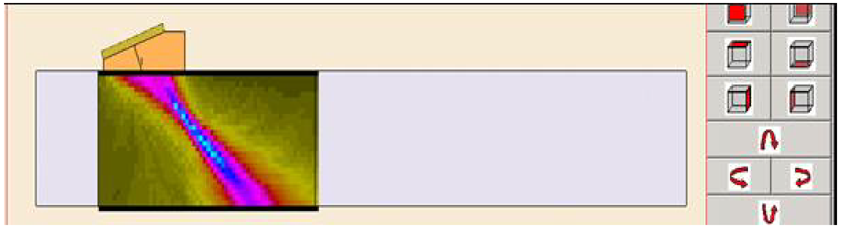
Questionable Detectability

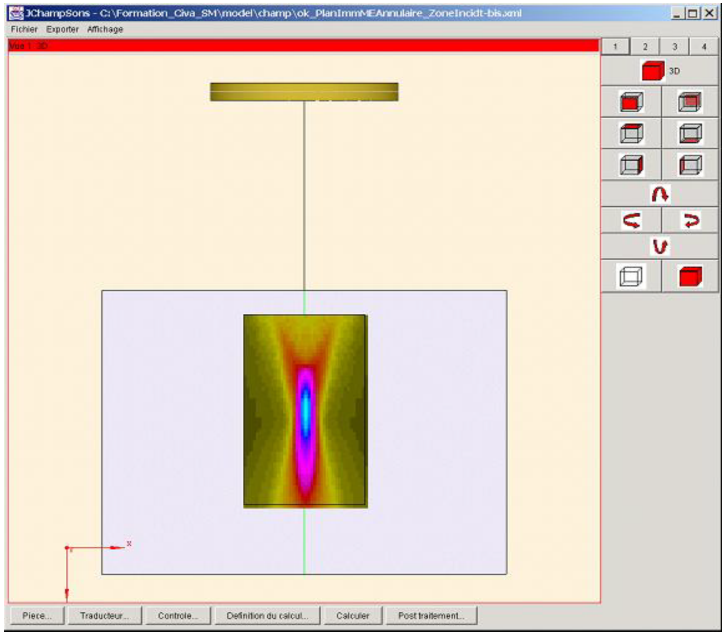
Images courtesy of NDTEducation

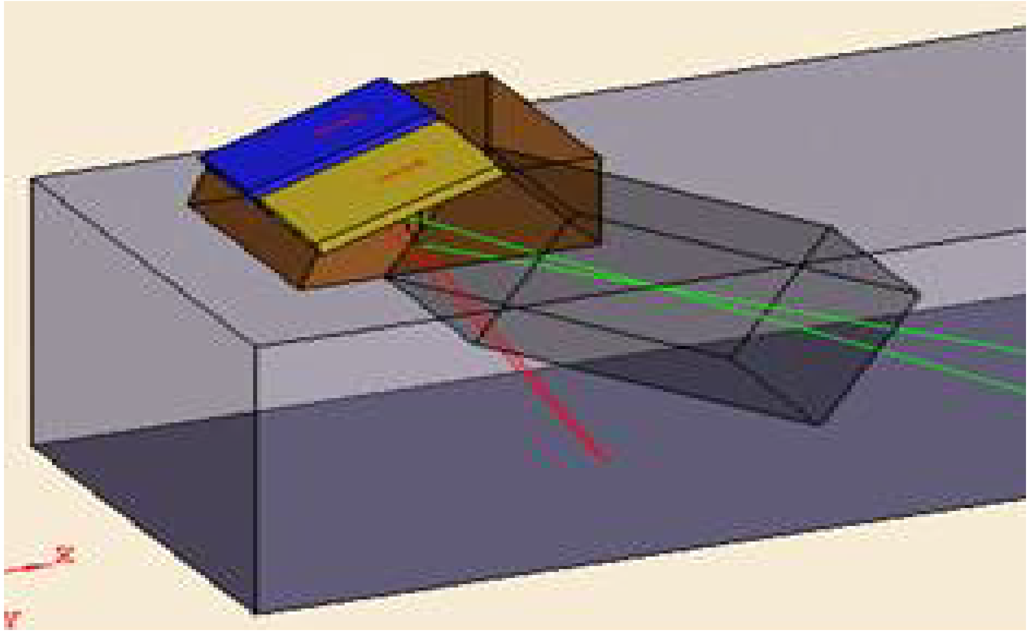
UT Modeling

- PA Contact Probe
  - Angle Steering and Focusing



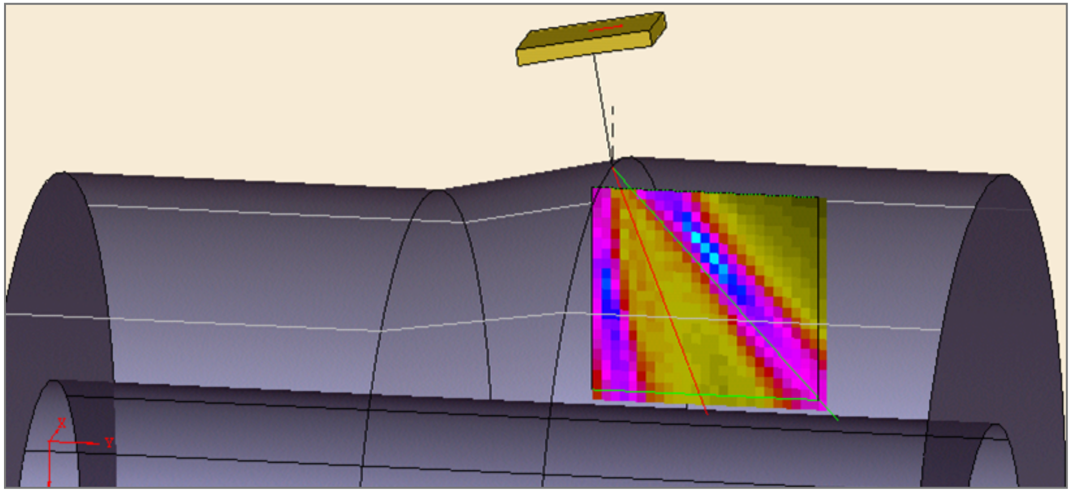


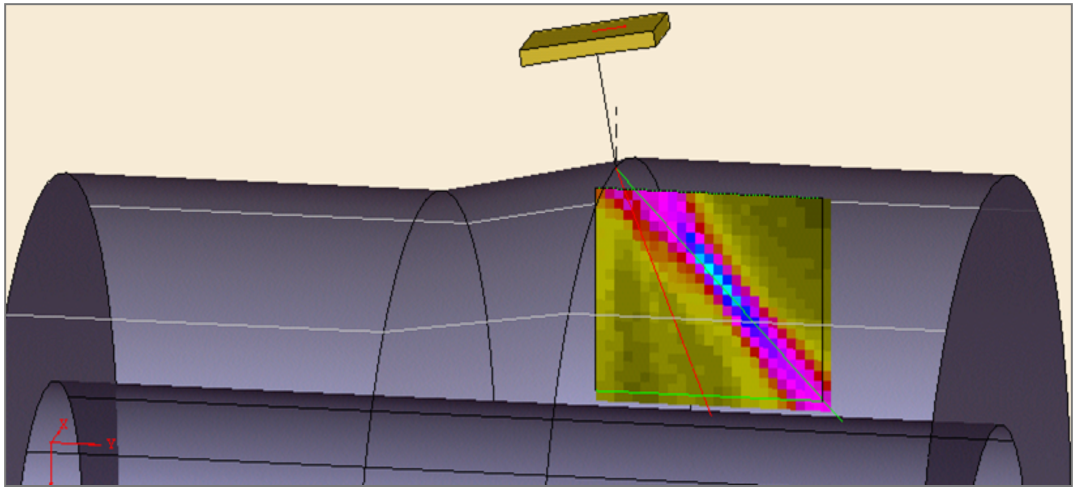




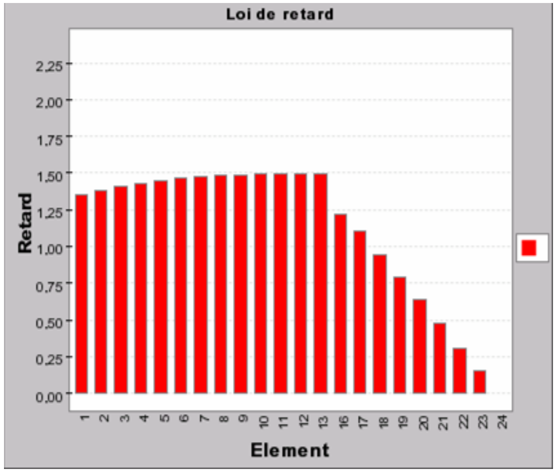
UT Modeling of Complex Part

Misaligned specimen (2.5D-CAD specimen with revolution)



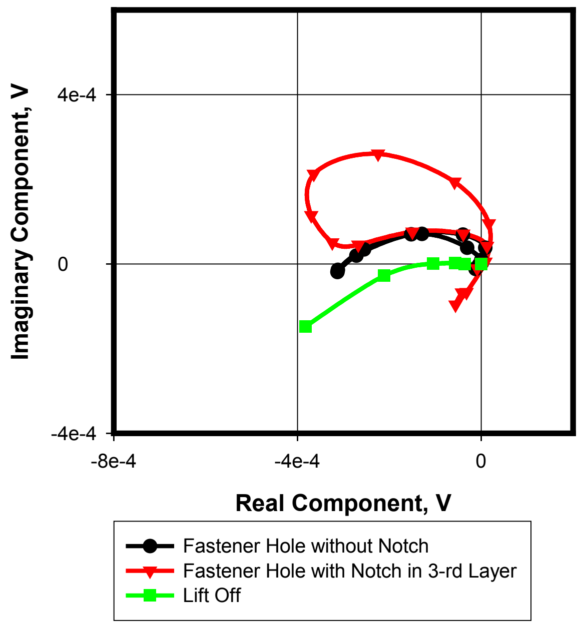


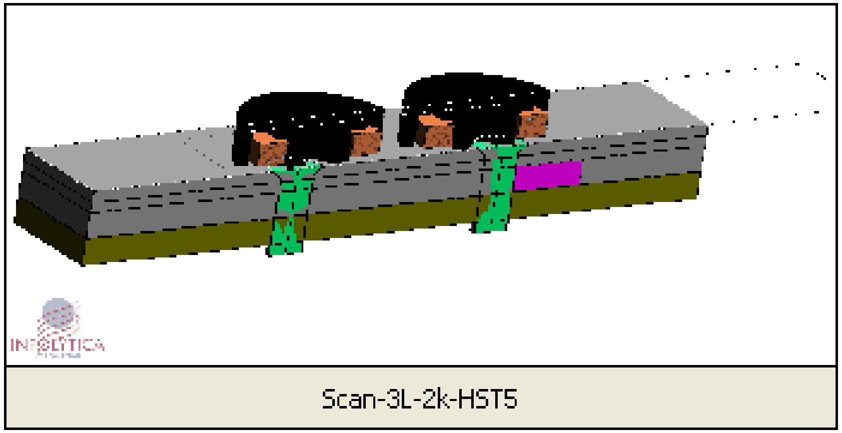
Customized PA Delay Laws Compensate for Component Geometry Effect

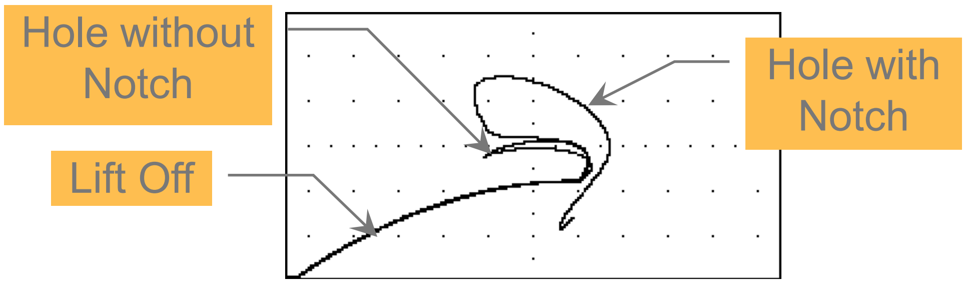


ET Modeling – Multilayer Subsurface

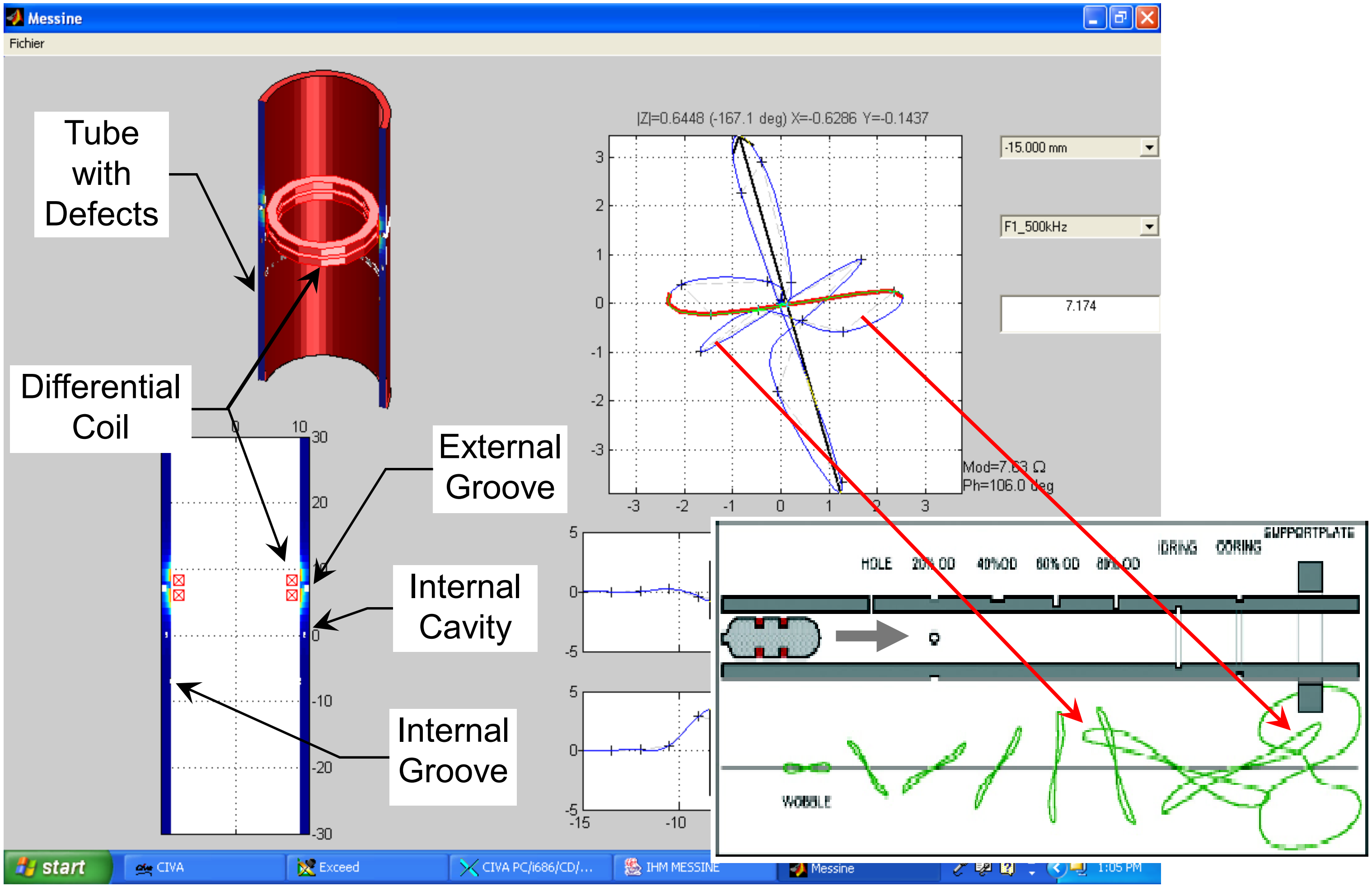
- Sliding probe and inspection area with fasteners are modeled for the first time in NDE industry
- Modeled signals compared well with actual signals







ET Modeling - Inconel Tube Testing

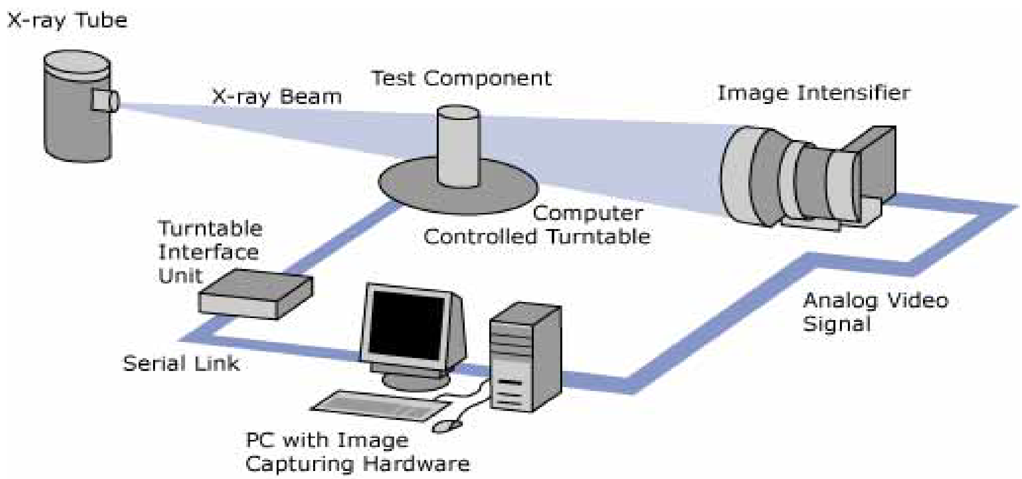


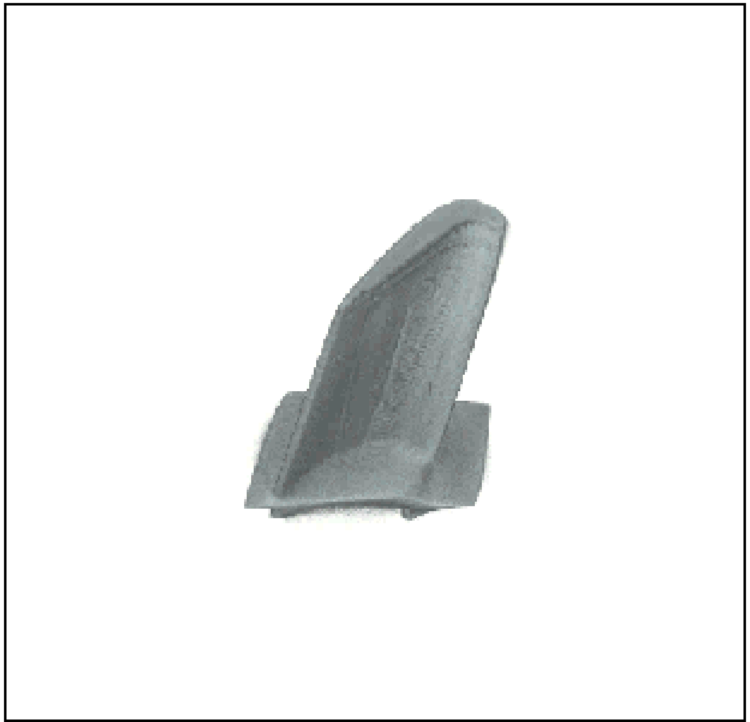
New Developments

- New developments broaden the applications, reliability, and accuracy of NDE techniques
  - Computed tomography
  - Phased array ultrasonics (PA UT)
  - Advanced array eddy current (AEC)
- The NDE becomes more quantitative than qualitative process

Computed Tomography (CT)

- CT Scan of Turbine Blade

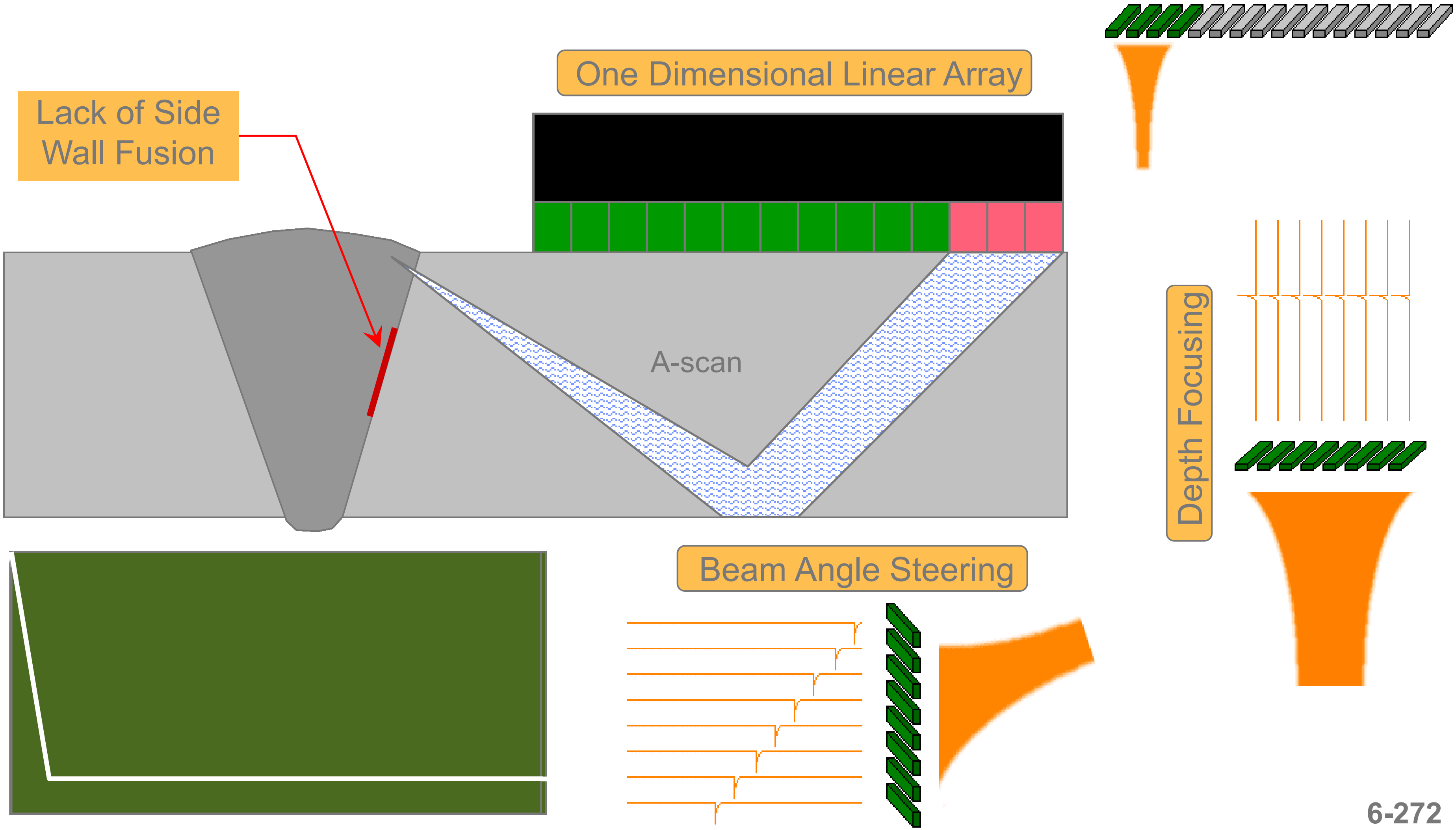




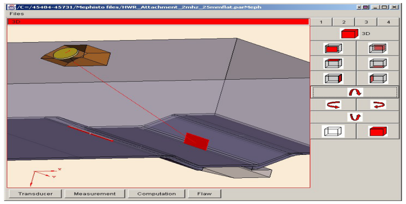
BladeAnimAVI

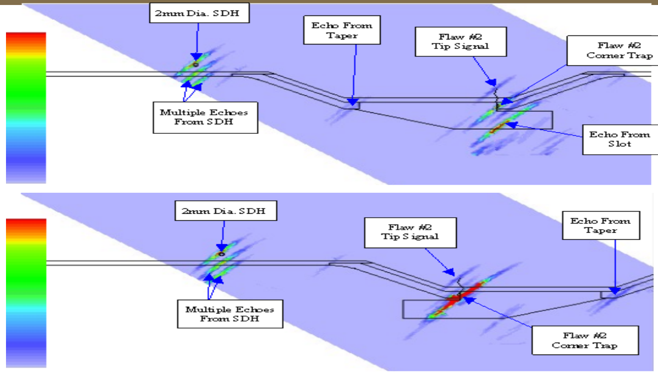
Image courtesy of NDTEducation

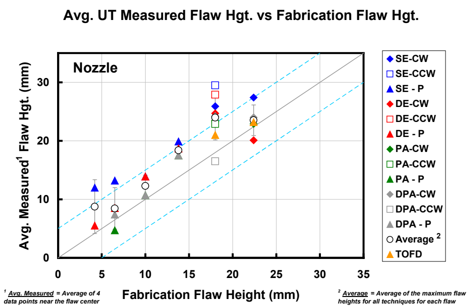
Ultrasonic Phased Arrays (PA) Techniques

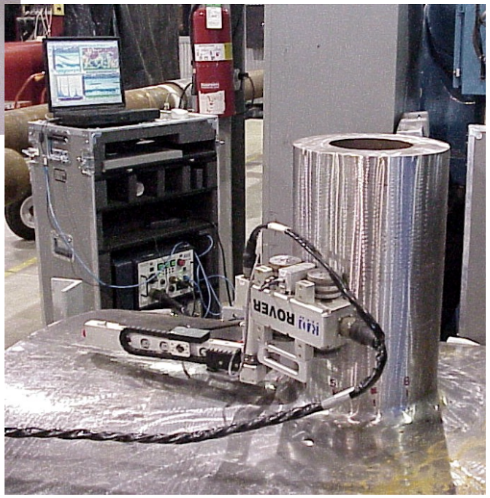


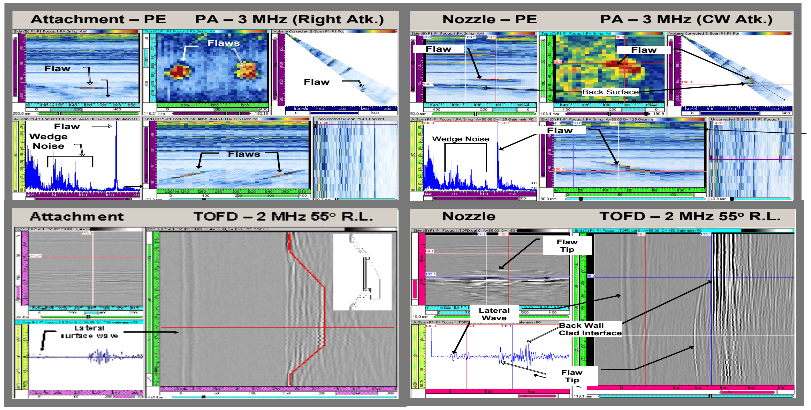
PA UT & TOFD for Cr-Mo Heavy-walled Reactors





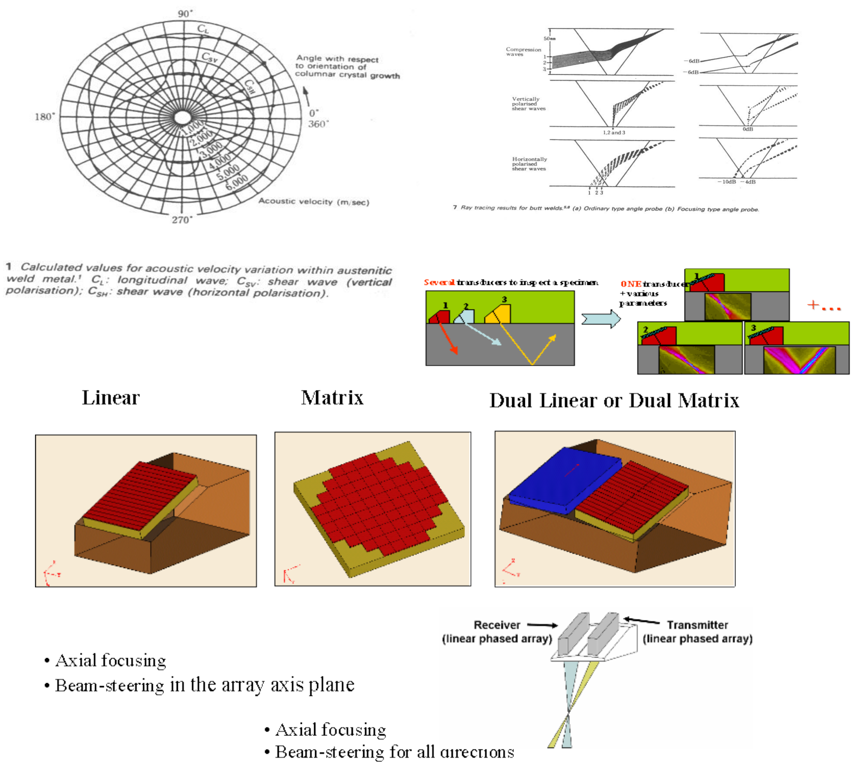


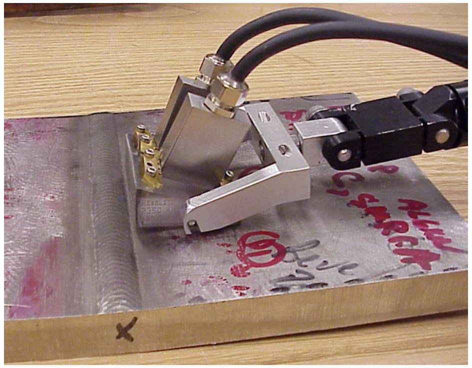


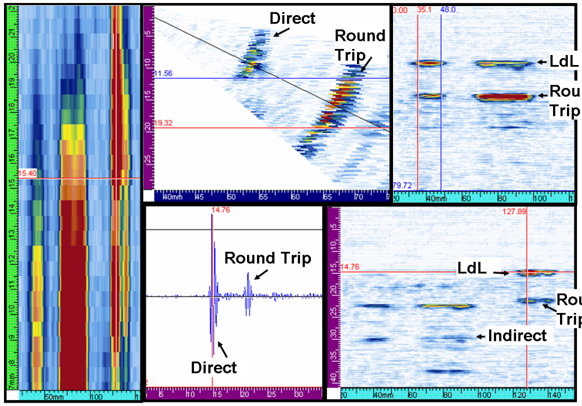


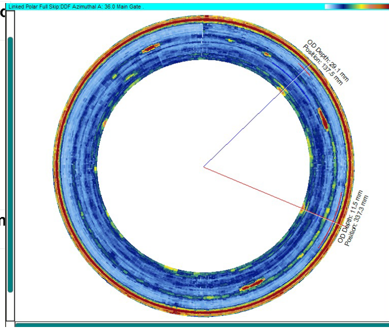
- Advanced UT modeling and simulation tools
- Optimized and implemented PA UT and TOFD for nozzles and attachments in 100-300 mm heavy-walled clad reactors

PA UT for Austenitic and Dissimilar Welds







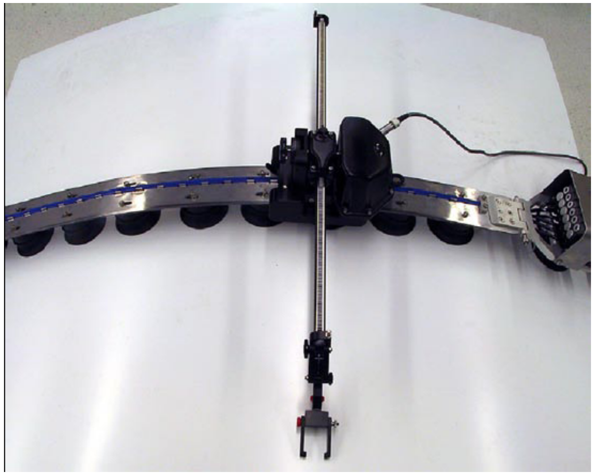


- Developed dual phased array technology
- Better inspections of large grain, highly anisotropic materials, dissimilar steel welds and nickel based alloys

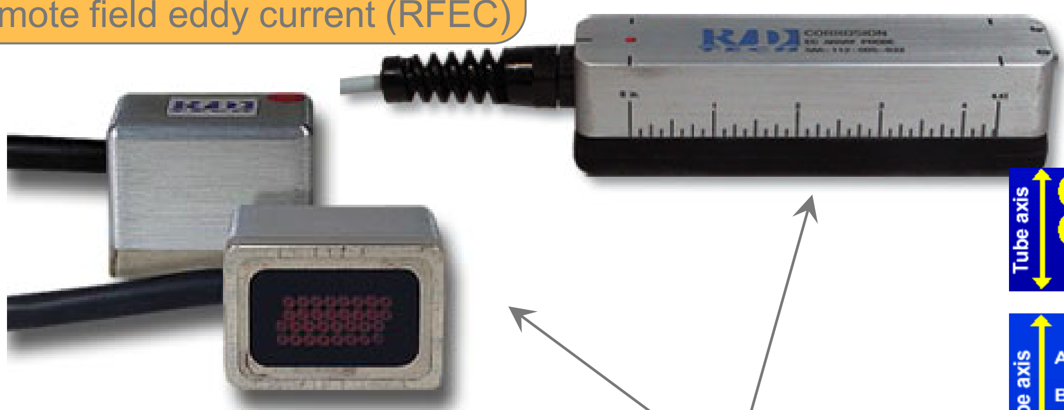
Eddy Current Multipurpose Array Systems

Up to 64 coils and 256 channels for conventional, array EC, magnetic flux leakage (MFL) and remote field eddy current (RFEC)

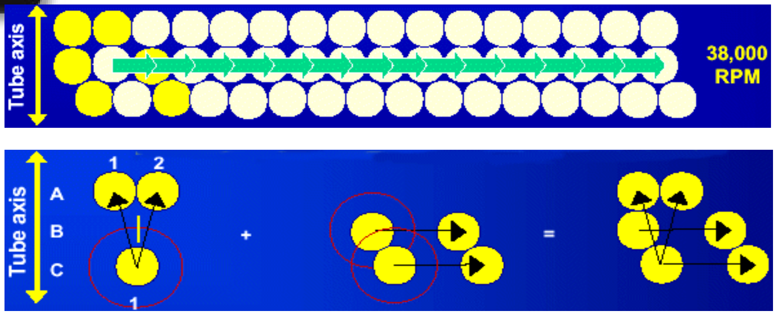
Portable eddy current array system for up to 32 coils



Scanner for Curved and Flat Surfaces

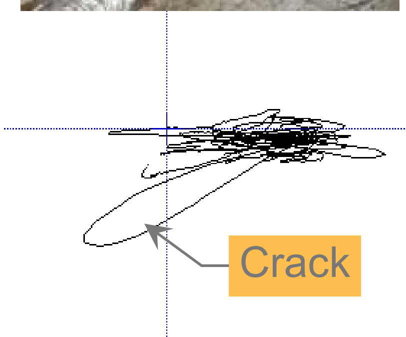


Array EC Probes



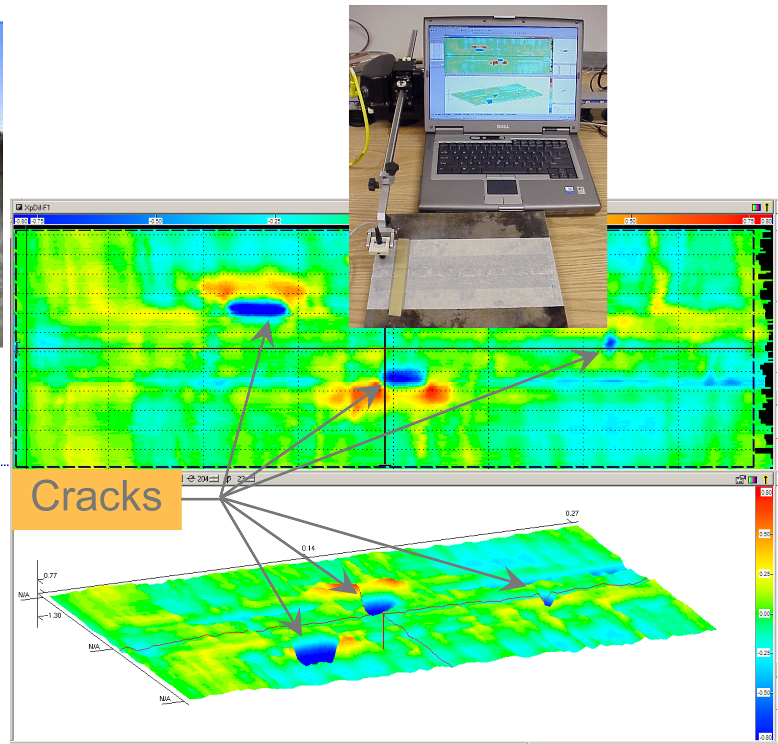
Conventional versus Advanced Eddy Current Techniques

Conventional Probe and Crack Indication



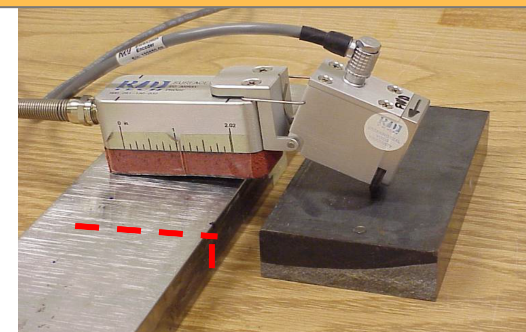
- Slow scanning
- Unreliable detection and sizing

Advanced Imaging - Same Probe and 3 Crack Indications



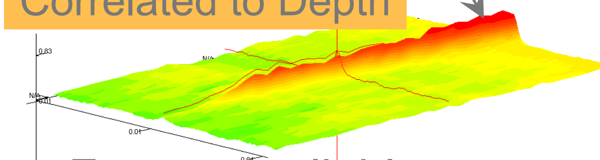
- Reliable detection flaw sizing

Fast Advanced Processing - Array Probe and Crack Indication



Crack in LF sample similar to crack in RH sample (sectioned)

Crack Indication Correlated to Depth



- Fast and reliable detection and flaw sizing

NDE Qualification

Module 6C

Outline

- Definitions
- Inspection background
- NDT personnel certification
- NDT procedures, qualification process and standards
- Specimens for POD and sizing
- POD and modeling for validation
- Inspection reliability
- Qualification standards, summary and references

Definitions

- ASME BPVC, Section V, Article 14
  - Examination System
  - Performance Demonstration
  - Qualification
- Qualification requirements for ultrasonic examination systems in ASME BPVC, Section XI, Appendix VIII, Article VIII-3000

Inspection Background

- Reason(s) for performing NDT
  - In-process, final, and in-service inspection
- Type(s) of flaws of interest in the object
  - Volumetric or planar
- Size and orientation rejectable flaw
  - Code, standard, other requirement
- Anticipated location of the flaws of interest in the object
  - Surface and subsurface
- Size and shape of the object/part
  - Simple, complex, large, small, sheet, tube, sphere, etc.
- Characteristics of the material to be evaluated
  - Density, roughness, paint, coating, electrical and thermal conductivity, magnetic permeability, tight or open cracks

NDT Personnel Certification - ASNT SNT-TC-1A

- Recommended Practice No. SNT-TC-1A: Personnel Qualification and Certification in Nondestructive Testing.
  - Provides guidelines for employers to establish in-house certification programs.
  - Provides the general framework for a qualification and certification program.
  - Provides recommended educational, experience and training requirements for the different test methods.

Other ASNT Standards and Guidelines for Nondestructive Testing Personnel

- ANSI/ASNT CP-189-2006
  - ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel.
- ANSI/ASNT ILI-PQ-2005
  - In-line Inspection Personnel Qualification and Certification
- ANSI/ASNT CP-105-2006
  - ASNT Standard Training Outlines for Qualification of Nondestructive Testing Personnel

Other ASNT Standards and Guidelines for Nondestructive Testing Personnel

- ANSI/ASNT CP-106-2007
  - Nondestructive Testing - Qualification and Certification of Personnel
- ASNT CP-107-2007
  - ASNT Standard for Performance-Based Qualification and Certification of Nondestructive Testing Personnel

NDT Procedures

- Most in accordance with ASME Section III, V and XI as applicable
  - UT examination of vessel and piping welds - ASME Section XI, Appendix III, Article III-2300
    - Weld types
    - Scanning surface and surface conditions
    - Equipment list
    - Examination technique
    - Calibration techniques
    - Calibration block design
    - Data and method of recording, interpretation of indications (III-4510)
    - Techniques for data interpretation and plotting
    - Personnel qualification requirements

NDT Procedures

- Separate articles dedicated to Calibration (III-3000) and Examination (III-4000)
- Important to identify correct standard/specification and technique Essential Parameters

NDT Qualification Process

- Input inspection data
  - What to inspect, flaw size location, orientation, detection and sizing capabilities to be demonstrated
- Technical justification (in some codes)
  - Review of NDE procedure, essential parameters, personnel qualification, previous experience, mathematical modeling, determine scope of qualification
- Specimen preparation (if needed)
  - Special requirements for flaw sizes, location, spatial and size distribution, number of units with and without flaw, specimen quality provisions

NDT Qualification Process

- Trials with specimens
  - Open and blind depending on requirements and inspection criticality
- Processing of data and making decision regarding adequacy of inspection equipment and procedure and/or personnel to perform to required level
  - Inspection objectives were met or were not met
- Quality assurance procedures for qualification process control
  - Issue of certificates, conditions for certification and recertification, specimen storage and access etc.

How Many Specimens Are Needed?

- ASME BPVC, Section XI, Appendix VIII
  - Supplement 2&3 – Wrought austenitic and ferritic piping welds
    - 3 personnel qualification sets for initial procedure qualification (detection)
    - 1 personnel qualification set for qualifying change of essential parameter
  - Supplement 4 – Clad/base metal interface of reactor vessel
    - 3 personnel qualification sets for initial procedure qualification (detection)
    - 1 personnel qualification set for qualifying change of essential parameter
  - Supplement 10 – Dissimilar metal piping welds
    - 3 personnel qualification sets for initial procedure qualification (detection)
    - 1 personnel qualification set for qualifying change of essential parameter
- Special requirements for flaw location on ID, OD and mid wall

How Many Specimens Are Needed?

Confidence	Number of Misses	Number of Sectors with Flaws	
		POD 90%	POD 95%
90%	0	22	45
	1	38	77
	2	52	105
	3	65	132
	4	78	158
	5	91	184
	10	152	306
	20	267	538
95%	0	29	59
	1	46	93
	2	61	124
	3	76	153
	4	89	181
	5	103	208
	10	167	336
	20	286	577

- ASME BPVC, Section V, Article 14 requires number of successfully detected flaws based on binomial law
- POD estimates are relevant for ONE FLAW SIZE ONLY
- Different number required depending on the POD and confidence
  - See table
- Number of flaws to be detected increases rapidly with increase of misses

How Many Specimens Are Needed?

- European Methodology for Qualification of Non-destructive Testing (EMQNDT), Issue 3
  - Not specific on number of flaws
  - Depends on criticality
- MIL-HDBK-1823 (latest 2007 draft)
  - At least 60 (ideally 120) flaws are required to build a reliable POD(a) curve when the hit/miss approach is implemented
  - At least 40 flaws are required to build a reliable POD(a) curve when $\underline{\hat{a}}$ vs. $\underline{a}$ approach is implemented because additional information is available
  - In addition, other conditions (linearity, error normality, adequate size selection, uncorrelated measurements and uniform variance) shall be verified to ensure that POD(a) estimate is valid

Issue of Flaw Sizing Qualification

- ASME BPVC, Section XI, Appendix VIII
  - Uses root mean square (RMS) sizing error to accept or reject a qualification test
    - m_i – measured flaw size
    - t_i – true flaw size
    - n – number of flaws measured

$$RMS = \sqrt{\frac{\sum_{i=1}^{n}(m_i - t_i)^2}{n}}$$

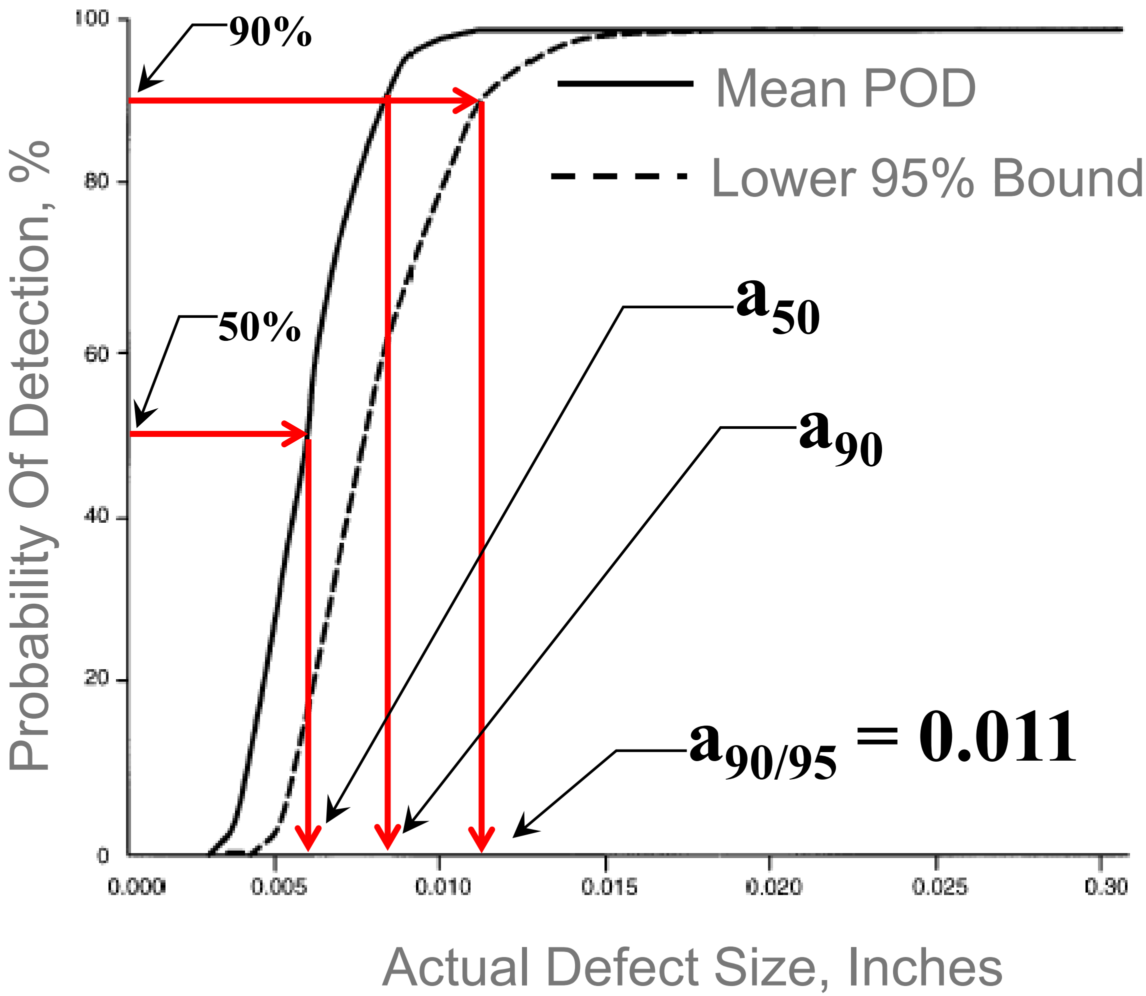
POD for Validation

- Weld flaws exhibit high variability
- Numerous factors may cause POD to vary widely
- Any POD data is specific to the application and conditions during test
- POD validation
  - Concept of POD introduced in 1973 by NASA on shuttle program
  - Similar requirements initiated by USAF
  - The concept later received widespread adoption for quantifying and assessing of NDE capabilities

POD for Validation

- ASME BPVC, 2008a Section V, Article 14
  - Defines POD as proportion of flaws detected to all flaws examined. Binomial law used for POD of similar flaws
- MIL-HDBK-1823
  - Defines POD as function of flaw size (length or height or other parameter) and uses non linear regression for POD estimate

Typical POD Curve vs. Defect Size



- Defect size of 0.011" is a90/95 it has 90/95 POD
  - 90% of defects 0.011" and larger are detected with 95% confidence (in 95% of the cases)
- a90, a50 are also used for system assessment

Modeling for Verification and Validation

- ASME BPVC, Section XI, Nonmandatory Appendix M
  - Models are to have limitations known, performance verified, and results accepted if difference with known solutions is less than +/- 10%
- ASME BPVC, Section V, Article 14
  - Modeling mentioned as part of technical justification (TJ)
- ENIQ, Recommended Practice 6, Report No. 15, EUR EN 19017
  - Use and validation of models as part of TJ discussed in more details
- MIL-HDBK-1823 (latest 2007 draft), Appendix H
  - Model applications discussed related to Model Assisted determination of POD (MAPOD)
- See previous section on modeling in RT, UT and ET

Factors Affecting Inspection Reliability

- Individual inspectors/human factors – experience, education, age, physical condition, attitude, and concentration
- Equipment – accuracy, sensitivity, analysis capability, versatility, portability, availability
- Procedures - simple and complex, general and specific, easy or difficult to follow
- Environment - production or in-field, laboratory or workshop, day or night, slow or fast paced, indoor or outdoor, in air (e.g., airborne, space, etc.), land, sea or underwater, accessibility

Inspection Reliability Improvement

- Establish and maintain personnel certification system
  - Central or employer based
- Use of readily available off-the-shelf equipment with well established capabilities
- Verification of procedure performance at the environment where it is expected to be carried out
- Use of procedure performance indicators
  - Computer modeling, probability-of-detection (POD) curves, experimental data, past experience, industry data and specifications, expert judgment, etc.
- Conducting performance demonstration (PDI) or NDE qualification programs for selected techniques, equipment and personnel
  - Trails with actual specimens
  - Sometimes qualification is based solely on technical justification (past experience, modeling etc.)

NDE Qualification Standards

- NRC Specifications and Procedures
  - NRC Inspection Manual
- ASME BPVC, Section XI – Rules for In-service Inspection of Nuclear Power Plant Components
  - Appendix VIII – Performance Demonstration for Ultrasonic Examination Systems
- ASME BPVC, Section V – Nondestructive Examination
  - Article 14 – Examination System Qualification
- Others
  - European Methodology for Qualification of Non-destructive Testing (EMQNDT), Issue 3, European Network for Inspection Qualification (ENIQ) Report No. 31, EUR EN 22906
  - MIL-HDBK-1823, Nondestructive Evaluation System Reliability Assessment, Department of Defense Handbook

Summary of NDE Qualification

- Reference appropriate ASME document
- Verify input information
- Clarify NDT specifics
- Use techniques with established capabilities
- Perform NDT demonstration if needed

References

- ASME Standards
- ASM Metals Handbook, Volume 17, Nondestructive Evaluation and Quality Control
- MIL-HDBK-1823, Nondestructive Evaluation System Reliability Assessment
- ASTM Standards, Section 3, Metals Test Methods and Analytical Procedures, Volume 03.03, Nondestructive Testing

ASME Section XI – Rules for Inservice Inspection of Nuclear Power Plant Components

Module 6C

Prabhat Krishnaswamy
Dr. Gery M. Wilkowski
Engineering Mechanics Corporation of Columbus
3518 Riverside Drive – Suite 202
Columbus, OH 43221

ASME Section XI - Early History

- Early power plant designers used “high” standards so that passive components of reactors could operate for their life without attention.
- In 1966, the AEC (NRC) recognized an inspection program will be necessary for pressure-containing components.
- A committee was developed and accepted as a subgroup of the ASME Section III Boiler and Pressure Vessel Committee.
- ASME Section XI code was published in 1970, originally containing 24 pages of text.
    - Today, contains over 500 pages and covers Class 1, 2 and 3 systems primarily for light-water reactors

ASME Section XI – Rules for Inservice Inspection of Nuclear Power Plant Components

- Three divisions
  - Light-water cooled reactors (483 pages)
    - Subsections for light-water cooled reactors
      - IWA – General requirements
      - IWB – Requirements for Class 1
      - IWC – Requirements for Class 2
      - IWD – Requirements for Class 3
      - IDE – Requirements for Class MC
      - IWF – Requirements for Supports
      - IWL – Requirements for Concrete Components
      - Mandatory Appendices
      - Non-Mandatory Appendices
  - Gas-cooled reactors(2 pages)
  - Liquid metal cooled reactors (1 page)

IWA – General Requirements

- Points user to other Subsections (i.e., IWB-, IWC-, etc.)

- IWA-1000 – Scope and Responsibility
- IWA-2000 – Examination and Inspection
  - Duties, qualification, access for inspectors (Including NRC inspectors)
  - Examination methods (visual-VT, surface-MP/EC, volumetric-UT/R, alternative-AE; more details later)
  - Qualifications of Nondestructive Examination Personnel – ASNT qualified Level 1 < Level 2 < Level 3
  - Inspection program – (details later)
  - Extent of examination (excludes welds for repairs in base metals)
  - Weld reference system (i.e., 0-degrees is top of pipe)

IWA – General Requirements

- IWA-3000 – Standards for Examination Evaluation
  - Significant digits for limiting values
  - Flaw characterization (discussed later)
  - Linear flaws detected by surface or volumetric examination (more detail later)
- IWA-4000 – Repair/Replacement Activities
  - General Requirements
  - Items for Repair/Replacement Activities
  - Design
  - Welding, Brazing, Metal Removal, Fabrication and Installation
  - Examination and Testing
  - Alternative Welding Methods, i.e., temper bead welding for repair of ferritic materials to avoid post-weld heat treatment
  - Heat Exchanger Tubing – plugging, explosive welding, friction welds, etc.

IWA – General Requirements

- IWA-5000 – System Pressure Tests
  - General
  - System Test Requirements
  - Test Records
- IWA-6000 – Records and Reports
  - Scope
  - Requirements
  - Retention
- IWA-9000 – Glossary

IWB – Class 1 Components

- IWB-1000 – Scope and Responsibility
- IWB-2000 – Examination and Inspection
  - Preservice
  - Inspection Schedule
  - Examination and Pressure Test Requirements

IWB – Class 1 Components

- IWB-3000 – Acceptance Standards
  - Evaluation of examination results
  - Supplemental examinations
  - Standards
  - Acceptance Standards- Workmanship flaw tables
  - Analytical Evaluation of Flaws
    - 3610 – 4” and thicker ferritic steel components
    - 3620 – less then 4” thick ferritic steel components
    - 3630 – Steam generator tubing
    - 3640 – flaws in austenitic and ferritic piping
    - 3660 – RPV head penetration nozzle flaws
    - 3700 – Analytical evaluation of operating plant events
  - Non-Mandatory Appendix A, C, G, H, K, L, O, Q
- IWB-5000 – System Pressure Tests

IWC & IWD – Class 2 & 3 Components

- IWC-XXXX for Class 2 piping (39 pages)
- IWD-XXXX for Class 3 piping (10 pages)

- Generally IWC and IWD have much less detail than IWB, and IWC and IWD will frequently refer user to IWB.
  - Exception might be some criteria specific to Class 2/3 piping, i.e., flow-accelerated corrosion (FAC) also called erosion-corrosion.

Other Subsections

- IWE-XXXX for Requirements for Class MC and Metallic Liners of Class CC Components of Light-Water Cooled Plants (10 pages)
  - i.e., drywell containment vessel for BWRs (Oyster Creek corrosion)
- IWF-XXXX for Requirements for Class 1, 2, 3 and MC component supports of Light-Water Cooled Plants (6 pages)
- IWL-XXXX for Requirements for Class CC Concrete Components of Light-Water Cooled Plants (14 pages)
- Appendices
  - Mandatory (I-X)
  - Nonmandatory (A-R)

Inspections

- The Code allows option for inspection programs, but a 10-year interval was chosen based on historical failure rate data

TABLE IWB-2411-1
INSPECTION PROGRAM A

Inspection Interval	Inspection Period, Calendar Years of Plant Service	Minimum Examinations Completed, %	Maximum Examinations Credited, %
1st	3	100	100
2nd	7	33	67
	10	100	100
3rd	13	16	34
	17	40	50
	20	66	75
	23	100	100
4th	27	8	16
	30	25	34
	33	50	67
	37	75	100
	40	100	...

- Risk-based inspection currently being used to determine inspection frequencies of different components
  - Non-mandatory Appendix R

Inspection Methods

- Originally concerned with fatigue cracking.
  - Note, the design sections of the ASME Code are made for preclusion of overload failures of unflawed components and fatigue failures, not any other degradation modes.
  - SCC is much more common in nuclear plants – Code does good job in designing to avoid fatigue failures
- UT was chosen over RT for superiority in locating and sizing fatigue cracks
  - UT can be performed from one surface
  - Appendices were developed for techniques for improving UT reliability
    - Appendix I for Vessels in 1973
    - Appendix III for piping in 1975
    - Currently eight appendices for UT

Inspection of Class 1 Systems

- Systems subject to examination include;
  - Reactor coolant system (RCS)
  - Portions of the auxiliary systems connected to RCS
  - Portions of the Emergency Core Coolant System (ECCS)
- ISI requirements were developed during and after the design/order of most US power plants
- Prior to 1977
  - Only 5% of each circumferential and 10% of each longitudinal vessel weld was required
    - Except vessel-to-flange and head-to-flange welds
- After 1977
  - 100% of the length of 25% of piping circumferential welds, and all circumferential dissimilar welds are required to be inspected

Flaw Characterization

- If a flaw is found, it must first be characterized
- The code gives guidance in the form of figures for determining flaw size, etc. for analyses
- The figures are for all flaw types
  - Surface, subsurface, multiple, planar,non-planar, etc.

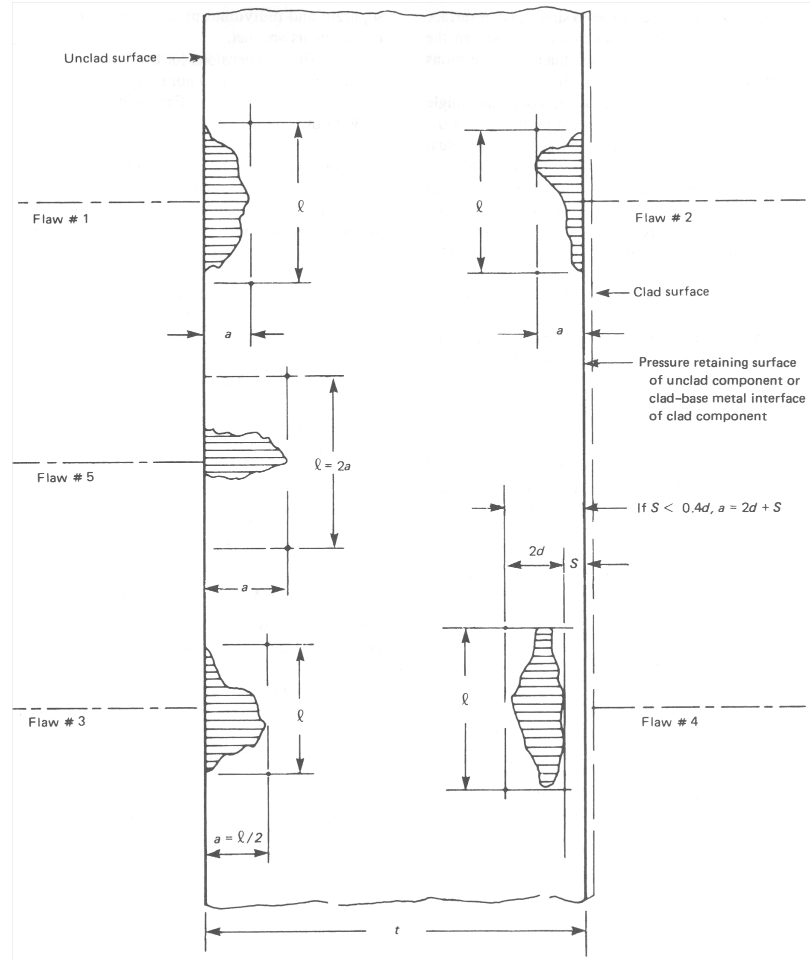


FIG. IWA-3310-1 SURFACE PLANAR FLAWS ORIENTED IN PLANE NORMAL TO PRESSURE RETAINING SURFACE
Illustrative Flaw Configurations and Determination of Dimensions a and ℓ
($\frac{1}{2}$ in. = 13 mm)

Flaw Characterization

- Spacing criteria (S) being updated
  - Flaw interaction difference for subcritical crack growth like SCC of fatigue cracks than for failure criteria

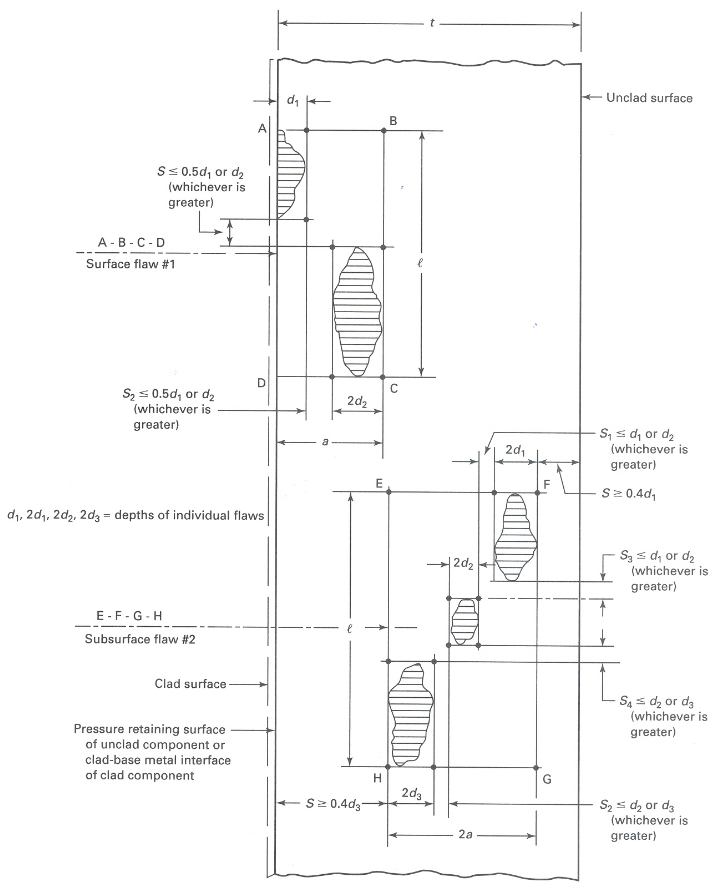
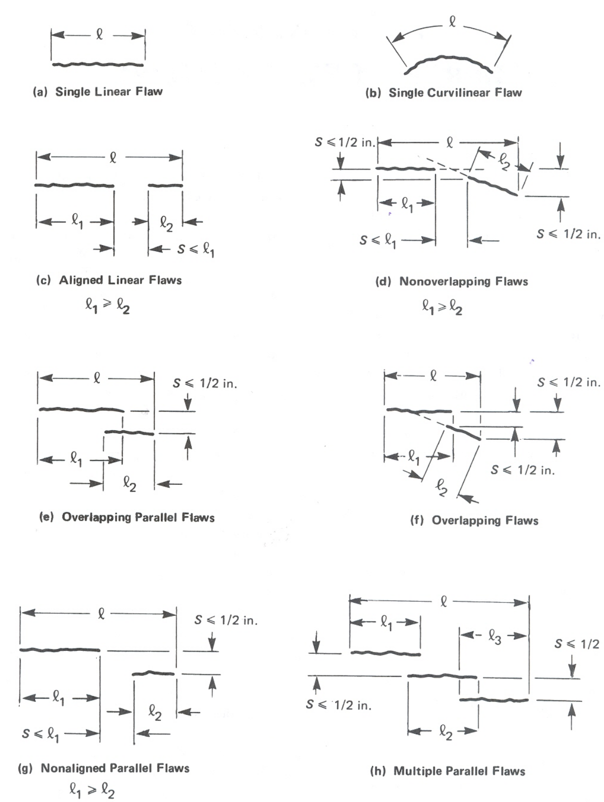


FIG. IWA-3400-1 LINEAR SURFACE FLAWS
Illustrative Flaw Configurations and Determination of Length ℓ
($\frac{1}{2}$ in. = 13 mm)



Flaw Acceptance Standards

- After the flaw is characterized, its size is compared with the Acceptance Standards
- These “Acceptance Standard” flaw sizes are also known as “Workmanship flaws”

TABLE IWB-3410-1
ACCEPTANCE STANDARDS

Examination Category	Component and Part Examined	Acceptance Standard
B-A, B-B	Vessel welds	IWB-3510
B-D	Full penetration welded nozzles in vessels	IWB-3512
B-F, B-J	Dissimilar and similar metal welds in piping and vessel nozzles	IWB-3514
B-G-1	Bolting greater than 2 in. (50 mm) in diameter	IWB-3515 IWB-3517
B-G-2	Bolting 2 in. (50 mm) in diameter and less	IWB-3517
B-K	Welded attachments for vessels, piping, pumps, and valves	IWB-3516
B-L-1, B-M-1	Welds in pumps and valves	IWB-3518
B-L-2, B-M-2	Pump casings and valve bodies	IWB-3519
B-N-1, B-N-2, B-N-3	Interior surfaces and internal components of reactor vessels	IWB-3520
B-O	Control rod drive and instrument nozzle housing welds	IWB-3523
B-P	Pressure retaining boundary	IWB-3522
B-Q	Steam generator tubing	IWB-3521

Flaw Acceptance

- Flaws that are smaller than these flaw sizes are acceptable for continued service without any evaluation
  - Tables being updated recently
- Flaws that are larger than the acceptable flaw size can either be repaired, or replaced, or found acceptable by analytical evaluation

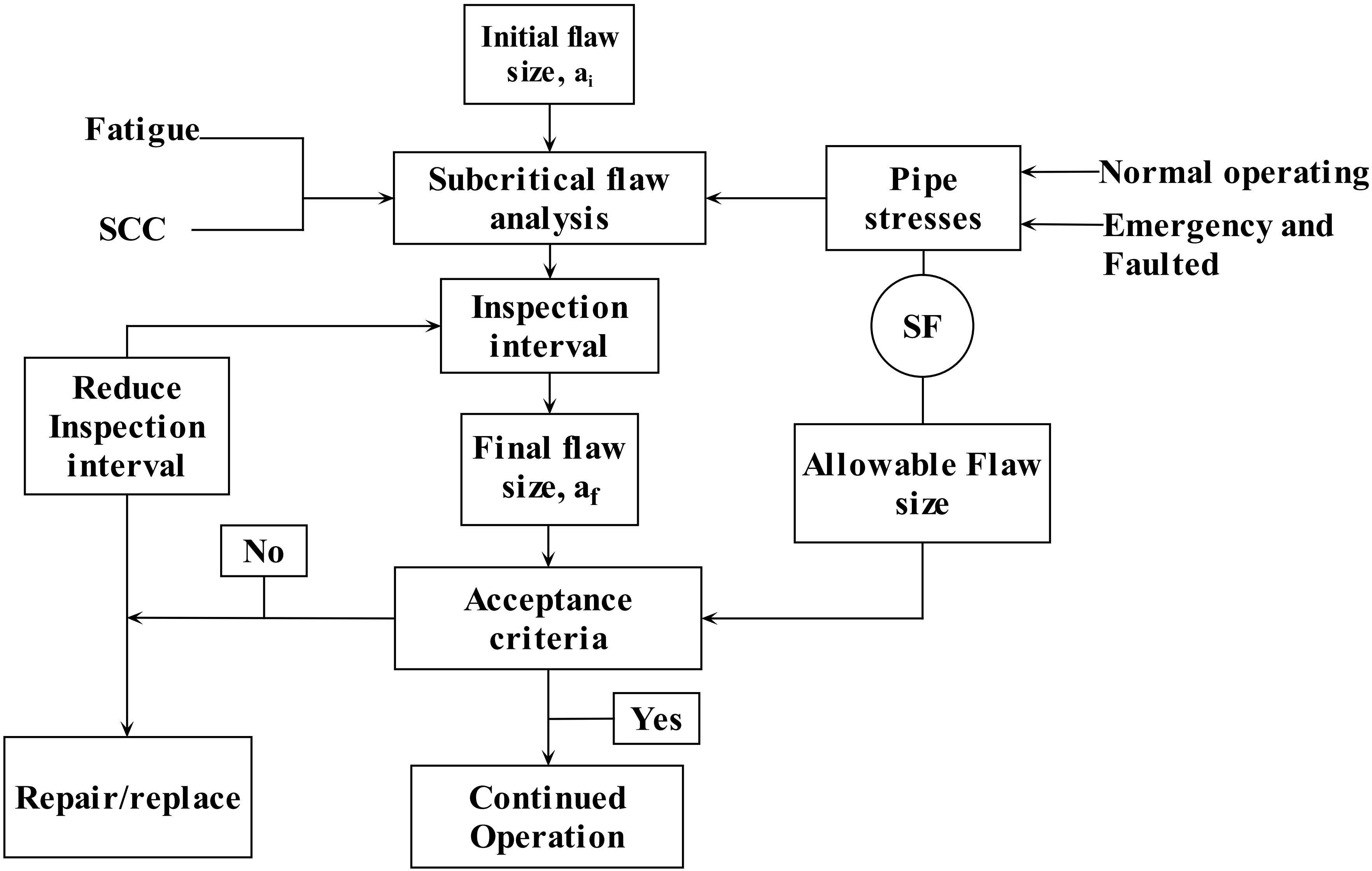
TABLE IWB-3510-1
ALLOWABLE PLANAR FLAWS
Material: Ferritic steels that meet the requirements of NB-2331 and G-2110(b) of Section III

	Volumetric Examination Method, Nominal Wall Thickness,[1,2] t, in. (mm)					
	$2^1/_2$ (65) and less		4 (100) to 12 (300)		16 (400) and greater	
Aspect Ratio,[1] a/ℓ	Surface Flaw,[5] a/t, %	Subsurface Flaw,[3,4] a/t, %	Surface Flaw,[5] a/t, %	Subsurface Flaw,[3,4] a/t, %	Surface Flaw,[5] a/t, %	Subsurface Flaw,[3,4] a/t, %
0.0	3.1	3.4 Y	1.9	2.0 Y	1.4	1.5 Y
0.05	3.3	3.8 Y	2.0	2.2 Y	1.5	1.7 Y
0.10	3.6	4.3 Y	2.2	2.5 Y	1.7	1.9 Y
0.15	4.1	4.9 Y	2.5	2.9 Y	1.9	2.1 Y
0.20	4.7	5.7 Y	2.8	3.3 Y	2.1	2.5 Y
0.25	5.5	6.6 Y	3.3	3.8 Y	2.5	2.8 Y
0.30	6.4	7.8 Y	3.8	4.4 Y	2.9	3.3 Y
0.35	7.4	9.0 Y	4.4	5.1 Y	3.3	3.8 Y
0.40	8.3	10.5 Y	5.0	5.8 Y	3.8	4.3 Y
0.45	8.5	12.3 Y	5.1	6.7 Y	3.9	4.9 Y
0.50	8.7	14.3 Y	5.2	7.6 Y	4.0	5.6 Y

Analytical Evaluation of Flaws

- The Code separates the evaluation of flaws into five categories
  - Ferritic components where t > 4 inches (102mm)
  - Ferritic components where t < 4 inches
  - Steam generator tubing
  - Ferritic and austenitic piping
  - PWR head penetration nozzles

Flaw Evaluation Flow Chart



Flaw Evaluation for Class 1 Piping

- The Code gives the user choices in evaluating flaws in piping
- If the flaws exceed the workmanship size flaws, they can be analyzed by;
  - Following the procedures in Nonmandatory Appendix C
  - Following the procedures in Nonmandatory Appendix H
  - Performing an alternate procedure, i.e., finite element analyses and demonstrating that the allowable loads have the following safety factors
    - Service level A – 2.7
    - Service level B – 2.4
    - Service level C – 1.8
    - Service level S – 1.4

Appendix C – Alternative Pipe Flaw Evaluation Criteria

- An Appendix C analyses has the following steps;
  - Determine flaw size
  - Resolve size into circumferential and axial components
  - Determine stresses normal to flaw for Service Level A-D
  - Perform a flaw growth analysis to determine flaw size at end-of-evaluation time period
  - Obtain material properties at operating conditions
  - Determine failure mode
  - Determine allowable flaw size or allowable stress (with appropriate safety factors)
    - Note the term “Safety Factor” is being changed to “Structural Factor”
  - Apply acceptance criteria
  - Recently updated for Dissimilar Metal Welds (In82/182 – SCC susceptible materials in PWRs.

Section XI Code Cases and Relief Request

- The Boiler and Pressure Vessel Committee meets regularly to consider proposed additions and revisions to the Code and to formulate Cases to clarify the intent of existing requirements or provide, when the need is urgent, rules for materials or constructions not covered by existing Code rules
  - ~200 code cases in existence (N-4 to N-759 as of 7/09)
    - ½ of them are for Section XI – rest for all other divisions of the code
  - More recent ones deal with evaluation of PWSCC cracking inspection, evaluations, and repairs, i.e.,
    - N-735 – Successive inspections of Class 1 and 2 pipe welds
    - N-740 – Dissimilar weld metal overlay for repair of Class 1, 2, and 3 items

Evolving Areas of Section XI

- Plastic pipe being approved for service water lines (Code Case N-755)
  - Next step is inspection and flaw evaluation – lack of fusion girth welds
- Buried service water line flaw acceptance criteria
  - Developing new procedures in Section XI for corrosion in steel buried pipes
    - Similar to natural gas/oil line issues, but level of tolerable leakage sensitive to contaminates in the line
- Gen IV reactors developing design criteria in Section III NH
  - Flaw acceptance criteria for creep/fatigue design may be in Section XI

Evolving Areas of Section XI

- Code is not based on guidance for avoidance of SCC (most common type of degradation mechanism in existing plant high energy systems) – needs some significant improvements!
  - SCC requires combination of material, water environment, high stresses
  - Usual cure is to change to a new material, try adjusting water chemistry, stress mitigation, repairs (overlays) or replacements
  - For new plant construction, need better guidance on how to fabricate welds with reduced or no tensile residual stresses on wetted surface of pressure boundary