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SPRING COLLEGE IN MATERIALS SCIENCE ON 'CERAMICS AND COMPOSITE MATERIALS'
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Background material for lectures on "NON-DESTRUCTIVE TESTING"

by

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Lecture Course on Non-Destructive Testing.

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Lecture topics.

Introduction to NDT.

Current scope, range of technology and its capability;
NDT/NDE and design, economic aspects.

Ultrasonic NDT.

The physics of ultrasound; practical ultrasonic NDT and its capability to detect and size defects.

Acoustic Emission.

Electromagnetic NDT.

An introduction and its capability to detect and size defects.

Radiography.

The basic radiography equations; its capability to detect and size defects.

Other NDT technologies.

Liquid Penetrant and Magnetic Particle Inspection.

Introduction to NDT.

Non-destructive testing (NDT) has been defined by the International Committee for NDT, in 1967, as; "A procedure which covers the inspection and/or testing of any material, component or assembly by means which do not affect its ultimate serviceability"

In addition to conventional NDT, which was established in its present form, by the 1960's, there is a development of a field of study known as "Quantitative Non-Destructive Evaluation" (QNDE). QNDE is a combination of science and technology that is moving NDT from being an 'art' to a science based sector of engineering which is integrated with design, materials science, component and system life evaluation and cost-risk analysis.

NDT can have several objectives which include material sorting, materials characterisation, property monitoring (for process control) and thickness measurement; however the major inservice task is;

1. Defect detection/location and ii, Defect characterisation.

A wide range of defects can be encountered and these depend on the particular type of component and material involved. Defects can include production flaws such as heat treatment cracks, grinding cracks, inclusions (of many types), and voids (pores) and service defects which tend to be in the form of corrosion or fatigue cracks. In many service situations it is the reliable detection and sizing of fatigue cracks which is the major task for NDT.

A major step forward has been the acknowledgement that every item contains flaws; these may be cracks several mm long or just micro-flaws in a crystal or at a grain boundary. The range of possible flaws and their effect on components should be considered from the design stage of a product.

NDT is now moving from being simply the detection of any defects, so that they can be removed or the part rejected (a zero-defects design philosophy); to NDE which includes consideration and evaluation of a design given that defects will be present (a Damage Tolerant Design).

Full advantage can only be made of results from stress analysis and fracture mechanics in a component life/failure model, if the presence of defects, the population of defects that is present, their location, type and dimensions are all accuratly determined. It is increasingly recognised that there must be 'Design for Testability' and 'Damage Tolerant Design' ; if the best possible or in some cases even adequate NDT is to be provided.

At the design stage information must be provided on;

1. Critical defect size must be calculated. (based on stress analysis and fracture mechanics)

2. An inspection limit must be selected for (a) fabrication quality control and (b) inservice inspection, giving defect types, size and inspection interval.

3. The capability of NDT must be known for the particular material, geometry and situation of interest.

4. The cost (and time required for) NDT, the value of the component and the added value that NDT/NDE give should all be quantified

Many of the NDT technologies are based on the interaction of some form of radiation with matter. (See Table 1) The resolution of NDT systems then depends largely upon the wavelength of the radiation and data can be used to give either an image of some form or an analysis based on the scattered radiation.

The orders of magnitude of critical defects in some materials are shown in Table 2. A comparison of selected NDT methods is given as Table 3.

In the U.K. a recent survey into NDT practice in industry has reported;

i. Weld inspection and weld testing were shown to represent major uses of NDT. When NDT is used 36% of firms had their own facilities but 86% made complete or partial use of NDT service companies.

ii. When the technologies used were considered it was found that for firms using NDT;
80% used radiography.
71 % used penetrant inspection
49% used MPI. (magnetic particle inspection)
and 49% used ultrasonics.

Of the NDT performed in industry probably more than 90% are manual operations. The remaining are a mixture of semi-manual and automated systems. The capability and costs, in terms of capital expenditure, of these various groups of inspections vary over several orders of magnitude. In addition to 'Industrial' NDT which can be performed on either production parts or as inservice inspections there is the 'Research' NDT/NDE which either seeks to provide methods to improve industrial performance or is part of a special research programme.

In the mid-1970's it was recognised that there was a lack of an adequate science base for NDT to become a quantitative science, in particular it was necessary to improve the reliability of inspections.

As a result of this realisation there has been a massive growth in NDT R&D in the USA and Europe since about 1974. Major progress has since been made to correct this through several research programmes including one sponsored through the USAF-DARPA which has looked at quantitative NDE required to meet aero-space needs and EPRI which has looked at the needs of the power generation industry . There have also

been major projects in Europe. The UK funding for NDT R&D is reported to have grown from about £ 0.5 M in 1974 to £15 M on research in 1981 with probably another £15 M for systems development. This growth has continued over the last six years. The factors which have contributed to the growth in NDT research are shown in Table 4.

In almost all the expanding NDT R&D projects work initially concentated on ultrasonics. It is now expanding to consider eddy-currents and more recently it has been widened further to consider most of the other NDT technologies and also a range of new materials. More than 60 % of QNDE Research over the last 10 years has concentrated on ultrasonics and it is in this field that the best science base has now been developed. Major progress is now also being made with other technologies.

If the current capability of various NDT technologies is considered it is found that no single figure should be used as the detection limit to characterise the capability. Such limits can however be established for specific NDT systems, applied to particular parts fabricated using a particular material. The best available data for steel was collected by 1974 and it is found that at least for laboratory inspection the capability has not changed significantly. (see Table 5) Of particular interest are the three headings under which the NDT techniques are given; (i) Test specimens, laboratory inspection, (ii) Production parts, production inspection and (iii) Cleaned structures, service inspection.

In some sense the data in Table 5 is presented in a simplistic fashion; the data is that for 25 mm ferritic steel samples with a surface 63 RMS, there are no details for the various forms of the technology that were employed, and the geometry involved is not specified. Also there is no consideration given to the ability to detect a range of possible inclusions which is of considerable importance for the inspection of components fabricated from materials such as a powder metal or ceramics.

A specific NDT technology or system is better characterised using a probability of detection (POD) curve. One set of examples of POD curves are given as Fig 1. This data provides a comparison of eddy current and other surface sensitive technologies. However no single POD curve is adequate to characterise a technology; as performance depends on material properties, part geometry and defect characteristics as well as the complete specification of the NDT system and the exact inspection technique employed.

Any evaluation of an NDT technology must include consideration of the human factors associated with its operation. For systems which employ human operators these human factor have been shown, in some cases, to be the cause of the largest single element in the uncertainty attached to detection capability and probability of detection determination. For example in one study by the USAF on aero-space components the data shown as Table 6 was obtained. From this USAF evaluation of NDT capability the data is in the form of the preliminary conclusions of the USAF 'ENSIP NDT' study and it is quoted as the detection capability achieved by the average of the majority and by the best 10% of technicians. Human factors are clearly an important consideration.

When the data shown in Tables 5 and 6 is compared the stated capability for the best inservice MPI and ultrasonic NDT are in close agreement. The Table 6 study found penetrant to perform significantly worse than would be expected from the Table 5 data; however the Table 6 eddy current performance was much improved and was closer to the laboratory inspection limit given in the Table 5 data.

In the last decade a much improved science base has been provided for the phenomena upon which the various NDT technologies are based. NDT has sought to move from being a qualitative to a quantitative technology and some statistics for probabilities of detection have been established.

To seek to improve the performance of NDT there is an increased use of automation and computer based technologies and in due course this will result in improvements in the capability of in-service inspections for use as part of life-extension or retirement for cause programmes. The basic flow diagram for a periodic inspection scheme is shown as Fig 2.

The NDT technologies selected for consideration in this short course are;

i. dye penetrants, and MPI, including automated systems.
ii. eddy-current and some otherelectromagnetic NDT technologies.
iii. ultrasonic NDT in various forms.
iv. radiography.

Four fundamental areas can be identified as the causes for the limitations on NDT capability:

i. The physics of the fundamental interactions.
ii. The instrumentation which is used.
iii. The inspection techniques, including human factors.
iv. The defect population; its range of types and sizes, base material properties and the component geometry.

From an engineering viewpoint the problems associated with the current NDT technologies have been summarised as;

1. Lack of NDT considerations at the design stage.
2. Inadequate 'engineering' of the NDT techniques.
3. Defect detection requirements which are often too close to the detection threshold.
4. Human factors in the inspection cycle.

The two lists of problems/limiting factors are complementary and are expressing the same problems from different viewpoints. It is also clear that effective NDT can only be provided if its requirements are an integral part of the design process. The ideal is that there should be design-for-testability; in practice the capability of NDT and its

limitations resulting from design decisions and their implications for the reliability of inspection need to be quantified. Increasingly computer based forward models are available to enable NDT to be evaluated on particular designs.

It would appear that the the major factors which limit the detection capability for laboratory NDT to the levels given in Table 5 are those of the interaction of fundamental physics with particular defect populations and material properties. In laboratory measurements the geometry tends to be simple, the surface finish is good and the quality of staff is high.

In the case of practical work performed in production or inservice conditions it would appear to be the instrumentation and the inspection techniques, including the human factors which are the more significant. Also in such situations the part geometry is more complex and small changes in geometry or material can have very significant inspection implications. The importance of human factors in field NDT is clearly indicated by the data given in Table 6.

The important area from the point of view of inspection in production and in-service is the NDT capability in these environments, which is seen to be significantly poorer than in the laboratory. (See Table 5) Three aspects of NDT performance are important and can be used to measure system performance and these are the probability of detection, minimum detectable defect and the sizing capability. The automation of conventional inspection has in general been found to improve repeatability of data collection and hence the POD through the reduction of the uncertainty introduced by inspectors. However automation todate has appeared in general to reduce the sensitivity of the detection capability measured in terms of the smallest detectable defect.

In most studies performance is specified in terms of a 'detection capability'. The problem of the false call, i.e. giving an indication when there is no real defect present needs further consideration. Also further work is required to consider the effects of the probability of NON-detection as it is this which gives the probability for the presence for the largest defect with particular characteristics which may be missed. This parameter is central to any fracture mechanics based component life evaluation; the NDT data for defect type, shape and size needs to be in a form in which it can be used in fracture mechanics calculations.

The motivation to perform NDT comes from the need for safety in industries such as nuclear power generation and aircraft and 'Quality' in general industry. The factors which have caused the growth are shown as Table 4 and it can be seen that the case for NDT is basically a case based on economics; either through the direct implications of quality or the need to ensure safety. By way of examples the figures for the costof shutting down a typical US nuclear plant for repair/inspection is $500,000 per day in terms of replacement power alone. The USAF retirement for cause which seeks to provide life extension for critical aero-engine components has been projected to be capable of saving the US $250,000,000 in terms of replacement part costs for the F100 engine. An increasingly important aspect of the economic case for NDT is Product Liability; the produce will have to pay if things go wrong and inspection technology was available and he simply did not use it. For much NDT a good economic case is available; a good case for the introduction or improvement of NDT can also be prepared for many products where current NDT is minimal. Probably the most convincing enconomic case has been presented for the USAF retirement for cause programme the projected cost savings for which are shown as Fig 3.

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Table 1. Comparison of mechanical wave and electromagnetic wave sources

*Type of energy**	*Frequency range* (Hz)	*Wavelength* (m)	*Photon energy* (eV)
1 Infrasonic	< 20	> 1.5 × 10^{2}	-
2 Audio	20–20 000	1.5 × 10^{2}–1.5	-
3 Ultrasonic	20 000–10^{9}	1.5–3 × 10^{-6}	-
4 Hypersonic	10^{9}–2 × 10^{12}	3 × 10^{-6}–1.5 × 10^{-9}	-
5 Radio frequency	10^{4}–54 × 10^{6}	3 × 10^{8}–5.5	
6 Ultra-high frequency (UHF)	54 × 10^{6}–4.7 × 10^{8}	5.5–0.64	3.33 × 10^{-11}–3.33 × 10^{-5}
7 Very high frequency (VHF)	4.7 × 10^{8}–1.3 × 10^{10}	0.64–0.03	
8 Microwaves	10^{10}–10^{12}	0.03–3 × 10^{-4}	
9 Infrared	10^{12}–4 × 10^{14}	3 × 10^{-4}–7.5 × 10^{-7}	3.33 × 10^{-5}–3.33 × 10^{-3}
10 Visible light	4 × 10^{14}–8 × 10^{14}	7.5 × 10^{-7}–3.75 × 10^{-7}	3.33 × 10^{-3}–1.33
11 Ultraviolet	8 × 10^{14}–5 × 10^{16}	3.75 × 10^{-7}–6 × 10^{-9}	1.33–2.67
12 Soft X-rays	5 × 10^{16}–3 × 10^{18}	6 × 10^{-9}–10^{-10}	2.67 to 1.67 × 10^{2}
13 Industrial X-rays and gamma-rays	3 × 10^{18}–3 × 10^{21}	10^{-10}–10^{-13}	1.67 × 10^{2}–10^{4}; 10^{4}–10^{7}

* Types 1–4: mechanical wave spectra (wavelength assumes velocity of 300 m s^{-1}); types 5–13: electromagnetic wave spectra (wavelength assumes velocity of light)

Table 2.

Materials		Flaw Size (mm)	Frequency for $\lambda_{\ell} = 2a_c$ (MHz)
Steels	4340	1.5	2.0
	D6AC	2.3	1.3
	Marage 250	5.0	0.59
	9Ni4Co 20C	27.5	0.10
Aluminum Alloys	2014-T651	8.0	0.4
	2024-T3511	25.0	0.26
Titanium Alloys	6Al-4V	8.0	0.375
	8Al-1Mo-1V(β)	14.5	0.21
Silicon Nitrides	Hot Pressed	0.05	100
	Reaction Sintered	0.02	250
Glasses	Soda Lime	0.001	2,500
	Silica	0.003	830

TABLE 3 —*Comparison of Selected NDE Methods*

Method	Properties sensed or measured	Typical flaws detected	Representative application	Advantages	Limitations
X-ray radiography	Inhomogeneities in thickness, density, or composition.	Voids, porosity, inclusions, and cracks.	Castings, forgings, weldments, and assemblies.	Detects internal flaws; useful on a wide variety of materials; portable; permanent record.	Cost; relative insensitivity to thin laminar flaws such as fatigue cracks and delaminations; health hazard.
Neutron radiography.	Compositional inhomogeneities; selectively sensitive to particular atomic nuclei.	Presence, absence, or mislocation of internal components of suitable composition.	Inspection of propellant or explosive charge inside closed ammunition or pyrotechnic devices.	Good penetration of most structural metals; high sensitivity to favorable materials; permanent record.	Cost; relatively unportable; poor definition; health hazard.
Liquid penetrants	Material separations open to a surface.	Cracks, gouges, porosity, laps, and seams.	Castings, forgings, weldments, and components subject to fatigue or stress-corrosion cracking.	Inexpensive; easy to apply; portable.	Flaw must be open to an accessible surface; messy; irrelevant indications often occur; operator dependent.
Eddy-current testing.	Anomalies in electric conductivity and, in cases, magnetic permeability.	Cracks, seams, and variations in alloy composition of heat treatment.	Wire, tubing, local regions of sheet metal, alloy sorting, and thickness gaging.	Moderate cost; readily automated; portable; permanent record if needed.	Conductive materials only; shallow penetration; geometry sensitive; reference standards often necessary.
Microwave testing	Anomalies in complex dielectric coefficient; surface anomalies in conductive materials.	In dielectrics: disbonds voids, and large cracks; in metal surfaces: surface cracks.	Glass-fiber-resin structures; plastics; ceramics; moisture content; thickness measurement.	Noncontacting; readily automated; rapid inspection.	No penetration of metals; comparatively poor definition of flaws.
Magnetic particles	Anomalies in magnetic field flux at surface of part.	Cracks, seams, laps, voids, porosity, and inclusions.	Castings, forgings, and extrusions.	Simple; inexpensive; senses shallow subsurface flaws as well as surface flaws.	Ferromagnetic materials only; messy; careful surface preparation required; irrelevant indications often occur; operator dependent.
Magnetic field testing.	Anomalies in magnetic field flux at surface of part.	Cracks, seams, laps, voids, porosity, and inclusions.	Castings, forgings, and extrusions.	Good sensitivity to and discrimination of fatigue cracks; readily automated; moderate depth penetration; permanent record if needed.	Ferromagnetic materials only; proper magnetization of part sometimes difficult.
Ultrasonic testing	Anomalies in acoustic impedance.	Cracks, voids, porosity, and and delaminations.	Castings, forgings, extrusions; thickness gaging.	Excellent penetration; readily automated; good sensitivity and resolution requires access to only one side; permanent record if needed.	Requires mechanical coupling to surface; manual inspection is slow; reference standards usually required; operator dependent.
Sonic testing	Anomalies in low-frequency acoustic impedance or natural modes of vibration.	Disbonds, delaminations, larger cracks or voids in simple parts.	Laminated structures; honeycomb; small parts with characteristic "ring".	Comparatively simple to implement; readily automated; portable.	Geometry sensitive; poor definition.
Ultrasonic holography.	Same as ultrasonic testing	Same as ultrasonic testing	Inspection of small, geometrically regular parts.	Produces a viewable image of flaws.	Cost; limited to small parts; poor definition compared to radiography.
Infrared testing	Surface temperature; anomalies in thermal conductivity and/or surface emmisivity.	Voids or disbonds in nonmetallics; location of hot or cold spots in thermally active assemblies.	Laminated structures; honeycomb; electric and electronic circuits.	Produces a viewable thermal map.	Cost; difficult to control surface emissivity; poor definition.
Strain gages	Mechanical strains	Not used for flaw detection	Stress-strain analysis of most materials.	Low cost; reliable	Insensitive to preexisting strains; small area coverage; requires bonding to surface.
Brittle coatings	Mechanical strains	Not commonly used for flaw detection.	Stress-strain analysis of most materials.	Low cost; produces large area map of strain field.	Insensitive to preexisting strains; messy-limited accuracy.
Optical holography	Mechanical strains	Disbonds; delaminations; plastic deformation.	Honeycomb; composite structures; tires; precision parts such as bearing elements.	Extremely sensitive; produces map of strain field; permanent record if needed.	Cost; complexity; requires considerable skill.
Leak detection	Flow of a fluid	Leaks in closed systems	Vacuum systems; gas and liquid storage vessels; pipage.	Good sensitivity; wide range of instrumentation available.	Requires internal and external access to system; contaminants may interfere; can be costly.

Table 4

Factors contributing to growth in NDT research

1 The increased worldwide attention being paid to nuclear reactor safety and consequent increased budgets available.

2 An increased awareness of the importance of plant safety and the consequent need for better "fingerprinting" and in-service monitoring procedures.

3 Political and social lobbying against pollution from pipelines and transport networks.

4 Tightening national economies and the associated need for higher quality products in competitive markets.

5 Sponsorship of "longer-look" research programmes (such as the DARPA/AFML and EPRI programmes in the States) and the consequent interests that have developed as a result in academic circles through sub-contract EMR programmes.

6 The setting up of national NDT research units (such as an NDT Centre at Harwell, IZfP at Saarbrücken and BAM in Berlin).

7 The general realisation that existing NDT technology has not been adequately linked to scientific advancements in contiguous fields — such as signal and data processing, medical diagnosis, seismic and geological surveying, pattern recognition and computer utilisation.

8 The understanding, from fracture mechanics considerations, that a proper assessment of materials integrity is dependent on quantitative data about defects and defect populations; as well as on parallel information about internal stress levels and local material property changes.

9 The fact that some of the newer constructional materials (such as composites and ceramics) have demanded a fresh approach to current NDT practices.

TABLE 5 Estimated variations in flaw detection limits by type of inspection (in mm) (in Pettit & Krupp, 1974).

NDT Technique	Surface cracks		Internal flaws	
	Processing	Fatigue	Voids	Cracks
Test specimens, laboratory inspection				
Visual†	1.25	0.75	*	*
Ultrasonic	0.12	0.12	0.35	2.0
Magnetic particle	0.75	0.75	7.5	7.5
Penetrant	0.25	0.5	*	*
Radiography	0.5	0.5	0.25	0.75
Eddy current	0.25	0.25	*	*
Production parts, production inspection				
Visual	2.5	6.0	*	*
Ultrasonic	3.0	3.0	5.0	3.0
Magnetic particle	2.5	4.0	*	*
Penetrant	1.5	1.5	*	*
Radiography	5.0	‡	1.25	*
Eddy current	2.5	5.0	*	*
Cleaned structures, service inspection				
Visual	6.0	12.0	*	*
Ultrasonic	5.0	5.0	4.0	5.0
Magnetic particle	6.0	10.0	*	*
Penetrant	1.25	1.25	*	*
Radiography	12.0	‡	4.0	*
Eddy current	5.0	6.0	*	*

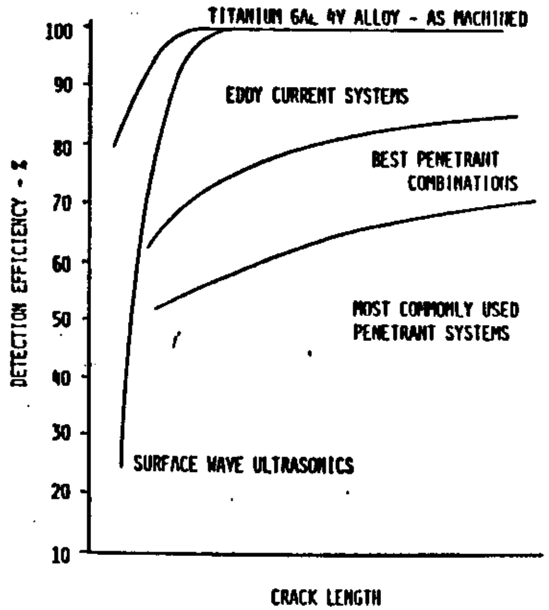
* Not applicable. † Use with magnifier. ‡ Not possible for tight cracks. (Based on 25-mm ferritic steel, surface 63 RMS.)

TABLE 6

Preliminary conclusions — Aero engine parts

	Average	Best	mm
Magnetic inspection POD	60% — .300" crack	65% — .250"	6.35
Penetrant inspection	90% — .220"	90% — .175"	4.45
Eddy current	90% — .090"	90% — .030"	0.76
Ultrasonic	80% — .375"	90% — .180"	4.57

- Average results obtained from majority of technicians
- Best results obtained from top 10% technicians



Comparsion of the typical detection performance of eddy current inspections with other surface sensitive processes

Figure 1.

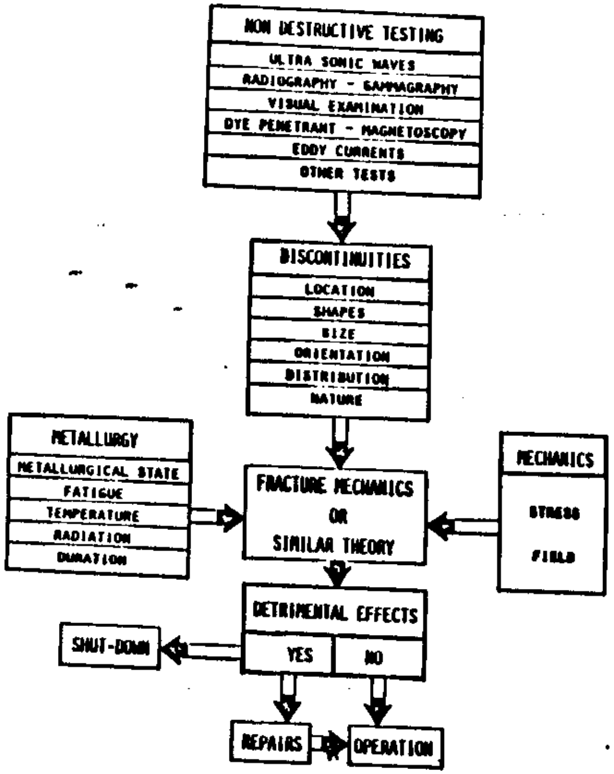


Fig. 2. Basic flow diagram for a periodic inspection.

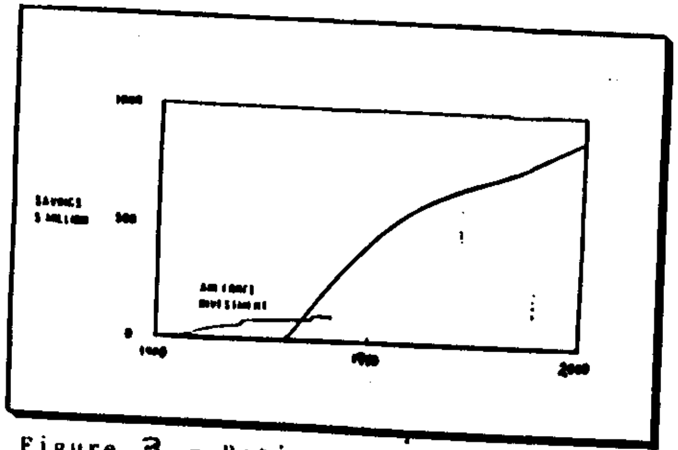


Figure 3 - Retirement For Cause Cost Savings

Ultrasonic NDT

The use of 'Ultrasonics' for defect detection goes back to the work of Sokolov in 1929 and Mülhauser in 1931. Of particular, significance was the work of Firestone (in USA) and Sproule (U.K.) in the early 1940's who introduced pulse-echo defect detection. Since about 1970 the subject has been undergoing considerable development of "quantitative" NDT techniques.

Ultrasonic inspection uses beams of high frequency sound waves to detect flaws in material. The input sound waves lose energy due to attenuation and on the interaction with 'features'. They undergo a mixture of;

1. Specular reflection
2. Mode-conversion
3. Diffraction from crack tips
4. Diffuse scatter from roughness

where 1 and 2 are well described by a series of plane waves reflected from plane surfaces and 3 and 4 are diffraction effects which in general are much weaker.

Sound is almost completely reflected at the metal-gas interface and partial reflection occurs at the metal/liquid and metal/solid non-metal interface. All types of features, cracks , pores, inclusions interact with the waves. This is especially so for features which have dimensions of the order of a wavelength.

Most ultrasonic NDT instruments, for use in metals, are based on monitoring one or more of the following;

1. Reflection of sound energy
2. Time of transit
3. Attenuation

and use frequencies between 1 and 25 MHz.

The frequency of sound used is determined by several factors including the size of defect of interest & the range required.

For a basic ultrasonic testing system, in the most general terms there are three elements;

1. Signal generation
2. Interaction with target
3. Signal detection.

Now consider this in more detail, looking at the elements in a two NDT set;

1. Signal/pulse generation
2. Transducer
3. Coupling layer
4. Waves generated by transducer, in object being tested.
5. Interaction with target
6. Scattered, mode-converted and diffracted wave field.
7. Coupling layer for receiver
8. Receiver
9. Amplifier
10. Display/analysis
11. Operator

The display of ultrasonic data can be in many forms, but tends to be one of three types; (Fig 4)

In view of all the potential complications, and before we take a close look inside the elements of the ultrasonic system what are the advantages of ultrasonic inspection as applied to metals.

1. Superior penetrating power (may travel 7m for axial inspection)
2. High sensitivity
3. Accuracy
4. For pulse-echo, only one surface need be accessible
5. Electrical system - suitable for scanning and in-line production control
6. Volumetric scanning
7. Not hazardous to health
8. Can be portable

From the potential advantages claimed for ultrasonic techniques it could appear that all testing needs could be met. Some have in the past and still do see ultrasonics as the answer. There are however some disadvantages which must be stressed;

1. Many systems; manual operation which requires careful attention by experienced technicians.

2. Extensive technical knowledge is required for the development of inspection procedures.

3. If parts rough, irregular, very small, thin or not homogeneous, they are difficult to inspect.

4. Discontinuities in shallow layers below surface may not be detected.

5. Couplants needed to get energy both in and out of part under test.

6. Reference standards are needed both for calibrating equipment and for characterising flaws.

Ultrasonic non-destructive testing, a more detailed look

In this presentation so far ultrasonic NDT has been considered in very general terms. We now take an increasingly close look.

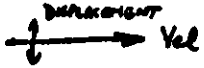
Basic waves

The elastic waves which are used in NDT are the same as those which are to be found in the literature of all the physical sciences, from seismology/geophysics, civil and mechanical engineering, and electrical engineering, as well as physics and applied maths and 'mechanics'. The common nature of elastic waves is presented in a recent article by Kraut (1976). (This paper includes an extensive list of general references).

There are four types of waves which are of interest in NDT;

1. Compressional (longitudinal) waves

2. Shear waves. Two forms; SH & SV.



3. Rayleigh (surface) waves.

4. Lamb (plate) waves.

For all these waves velocity, frequency and wavelength are related by;

$$V = f\lambda$$

Acoustic impedance

An important parameter which describes the response of a medium to an elastic wave is acoustic impedance.

$$Z = \rho V$$

where ρ density and V is velocity

Major variables in ultrasonic inspection

The major variables that must be considered in ultrasonic inspection include;

1. Characteristics of the ultrasonic waves.

2. Characteristics of the material under test.

These are taken together with the equipment used to accomplish different objectives.

Parameters determined by transducer, (or to large extent by transducer) shape (geometry) diameter etc.

1. Frequency. Set by disc, and the backing used.

2. Sensitivity, in detection. For high resolution use high frequency short wavelength, to keep wavelength feature size ratio about at least unity.

3. Resolution, to separate two defects. $\propto$ frequency bandwidth

   $\propto$ 1/pulse length.

4. Range reduced by high frequency (see note on attenuation).

5. Beam spread (or divergence). As frequency decreases the beam becomes more complex.

Beam Intensity

Intensity is related to the amplitude of partiticle vibrations. Acoustic pressure (Ap) is used to denote amplitude of alternating stress;

$$Ap \propto Z \times \left\{ \text{Amplitude of Motion} \right\}$$

Intensity is the energy transmitted;

$$I \propto (Ap)^2$$

Piezoelectric transducer elements sense Acoustic pressure. MOST ultrasonic sets are designed to give;

$$\text{Output Voltage} \propto \left(\text{Input voltage} \right)^2$$

Therefore in most systems;

$$\text{Voltage out} \propto (\text{Intensity})$$

N.B. It is acoustic energy and not acoustic pressure which is partitioned at an interaction.

Attenuation of ultrasonic beams

There are many factors which reduce the energy in an ultrasonic beam;

1. Transmission loses
2. Interference effects
3. Beam spreading

Also in real transducers there are losses due to generation of unwanted modes, coupling loses which greatly influence system response. The use of Schlieren and photoelastic techniques has demonstrated many of these problems. e.g. Hall (1976).

Waves at interfaces

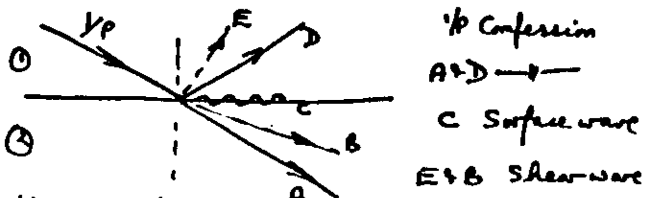
A major factor which influences the amount of energy which will pass through a structure is the reflection at interfaces. For normal incidence of flat wave fronts simple relationships exist for transmission and reflection;

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

$$T = \frac{I_T}{I_i} = \frac{4Z_2Z_1}{(Z_2 + Z_1)^2} \quad \text{where } Z = \rho V$$

For non-normal incidence the situation becomes more complex and mode-conversions can occur.

The basic angles are determined using Snell's Law, but the energy in each wave is not easily calculated. Formulations do exist, which are given in advanced texts (Ewing et al 1957), for waves in complex layered structures, but complete analysis is not available for many real situations.



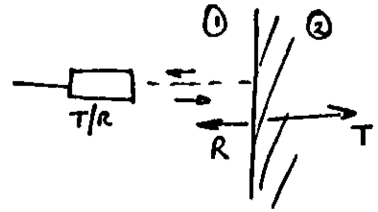
General non-90° incidence at an interface.

Examples of interface effects

1. The use of compressional waves in wedges is one method for the generation of both shear and Rayleigh waves. The angles required are determined by Snells Law.

For immersion testing of an Aluminium plate

2. At Water/Aluminium interface
   Rc = 71% Tc = 29%



Therefore the return form the back wall of a plate is 6% of original intensity.

For the case of a Carbon Steel plate the back wall echo intensity 1.3% of input.

For case of a Tungsten plate the back wall echo intensity is 0.3% of the input.

3. Contact Testing

i Back-wall echo is increased by 30%, and more if plate air backed.
ii Best coupling medium has higher acoustic impedance than water. Also must be a thin layer. ($\simeq \lambda/100$)

A basic text which considers these relationships for NDT (and the formulae for other NDT systems) is a BINDT Monograph edited by Halmshaw (1978)

Absorption

i Energy converted into heat due to elastic motion.
ii In polycrystalline media loss due to heat flow out of moving grains (low frequency).
iii Domain movements.
iv Loss due to inelastic motion.

In general absorption increases at high frequencies.

Scattering

This occurs because material is not truly homogeneous; i.e. crystal discontinuities, grain boundaries, inclusions etc. Effect is HIGHLY dependant on the relationship between grain size (d) and wavelength;

d less than 0.01	Wavelengths	No scattering
d greater than 0.1	Wavelengths	Scattering, and inspection may be impossible.

In general:- Scattering $\propto \left(\text{Grain Size}\right)^3$

Diffraction

In a homogeneous medium a sound beam is coherent. However, when an edge is passed interference effects occur. The effects which occur in ultrasonic wave systems are similar to those seen in optics.

Diffraction, and the resulting losses and noise signals, must be considered, but only qualitative guidelines can be provided. e.g. All roughness results in diffraction. This is of particular importance at interfaces.

For such features as a small hole a Huygen type source is observed. A transducer also has diffraction effects.

Attenuation

In most situations it is the overall attenuation which is of interest. This is because it is the overall figure which sets the limits to the depth of inspection at a particular frequency.

For example for 2MHz compression waves;

Inspection depth. (Metre)	Attenuation (dB/mm)	Media
1-10	0.001-0.01	Aluminium Steel
0.1-1.0	0.01-0.1	Cast Iron
0.-0.1	Above 0.1	Many non-metals

Overall attenuation $P = P_0 \exp(-\alpha L)$

where L - path length, α attenuation coeff.

Transducer wave fields (for disc transducers)

Real transducers do not act like piston sources, as this has been well demonstrated in visualisation studeies.

When the pressure field is investigated;
On the axis of a disc transducer get maxima and minima. (Nearfield

1. Near field length

$$N = \frac{(D^2 - \lambda^2)}{4\lambda} \simeq \frac{D^2}{4\lambda} \simeq \frac{A}{\pi\lambda} \quad \text{(for small dia)}$$

2. Beam spreading (Circular field)

$$\gamma = 68.8\,\lambda/D$$

Only valid for small λ/D i.e. small beam angle.

Pressure on axis of ideal transducer is well defined.

Contour plot shows approximate field shape. (Many transducers are VERY far from ideal).

Interaction with defects

The scattered, diffracted, transmitted and mode-converted field generated following the interaction of even a simple incident wave field with a target may be very complex. Even in the long wavelength limit the scattering data depens upon 22 properties of the scatter, which in the general case can be independent (Richardson 1978).

The major components in the scattered field result from;

1. specular reflection
2. mode-conversion
3. diffraction
4. diffuse scatter

In many structures the geometry will considerably influence the situation. i.e. a crack end on is a point scatterer, while the same feature side-on it is a specular reflector.

The understanding of the interaction of a particular wave/target interaction can be approached in several ways;

1. Analytical theory
2. Numerical models
3. Laboratory studies on 'ideal' features
4. Measurements on real features e.g. real fatigue cracks

Some standard references are to be found in the paper by Kraut (1976b) although advances are still being made.

Elastic wave scattering and diffraction

The theory for elastic wave scattering is at present far from adequate. A range of high and low frequency approximations, combined with numerical modelling can however provide much useful information.

Various reviews for the present state of the theory have been produced, and useful introductory reviews have been produced by Kraut (1976b) and Dean (1982).

Practical Ultrasonic NDT.

There are now a vast range of practical ultrasonic NDT techniques for defect detection and location, some of which also give defect sizeing and characterisation. The standard text on practical ultrasonic NDT is Krautkramer J & H, (1983).

These methods can be grouped in several way;

The simple testing configurations include, a single transducer in pulse-echo mode are shown in Fig 4 to give A,B, and C scans. A shear wave transducer in pulse-echo mode is shown as Fig 5. A transmission inspection method which uses two compression wave transducers is shown as Fig 6.

Such techniques can then be considered further in terms of the information collected and used;

1. Amplitude (the most commonly used data when combined with time)
2. Travel time or time-of-flight. (Shown in Fig's 7 and 8)
3. Spectroscopy. (frequency Content)
4. Mode-conversion or scattered waves. (wave type and changes in wave type).

The techniques can be considered as two gropus, defined in terms of how they are applied;

a. Contact testing (shown in the figures 5 above), which place a probe directly onto the object under test using a thin layer of couplant.
b. Immersion testing , which uses either a water bath or water jet to couple the fluid into the test object. (tends to be used at higher frequencies 10 MHZ + or when large areas are scanned with component in a water bath or when a squarter is employed.)

For sizing cracks using ultrasonic techniques there are;
i. Pseude-sizing techniques(give an acoustic size relative to a standard reflector).

(a) flat bottom hole. NB NOT A TRUE SIZE for the defect.

(b) measure distances of a scan and distance which signal is above a threshold. Better but tend to under estimate true geometric size. ($d > \lambda$)

ii. Accurate sizing (true geometric size of target)
(a) Probe displacement: ($d > \lambda$)
Measure & plot features at extreme ends of crack; 6 or 20 dB drop.
(b) time of flight; surface or body waves. (Best $d \gg \lambda$)
(c) Scatter analysis; Range of measurements at several angles range of frequencies.
(d) Inversion schemes; SPOT and Born inversion. ($d \approx \lambda$)

All ultrasonic NDT techniques are based on the interaction of ultrasonic waves with the component and any defects which may be present. The fundamental parameter for the ultrasound is then the wavelength (λ). As already indicated a wide variety of practical approaches have been developed to detect and size defects and these can be ordered in terms of the ratio of the flaw size to wavelength ratio as shown in Table 7. When the parameter ka is used the various scattering regiemes can be easily defined (k is the wave number and a is the characteristic dimension of the scatterer). The figure included with Table 7 shows the scattered amplitude for a range of ka for a sphere.

In general terms ultrasonic NDT is either based on 'Imaging' (Tittmann (1980)); see Table 8) or direct analysis of the reflected or scattered ultrasound. It is then the wavelength which limits the spatial resolution or spot size for a focused transducer. The physics of the forward scattering problem are now quite well established. (Thompson and Thompson (1985)) Problems do however remain for the theory for rough scatterers and those which contain many small pores.

Scattering interactions also depend on the ratio of the dimensions of the flaw (D) and the grain size (d) of the base material which determines the attenuation and grain scattering and their ratio with the wavelength.

D/λ can be used to characterise the defect response;

and D/d or d/λ can characterise the attenuation and scattering and in turn the signal-to-noise ratio for the system.

The other fundamental parameters which have already been discussed are the ratio of the shear and compression wave velocities (Vs/Vc) together with the acoustic impedances (Z) for the base material and their ratios with the corresponding parameters for any inclusions. The Vs/Vc ratio for the base material is of importance in the determination of the response for cracks and voids.

A wide range of theoretical developments have been made and models of a range of types can now be used in the design and validation of new NDE techniques. Current interest is in the extension of theory to cover more complex and rough scatterers and the solution of inverse scattering problems. A range of computer based forward scattering models have now been developed which can predict ultrasonic performance. The best modelsappear to be those produced at Ames Laboratory Iowa State University. (Thompson and Gray (1986)).

In many practical cases when conventional ultrasonic shear or compression wave techniques are employed for finished components it is the part geometry which limits the NDT capability. Another practical problem is the considerable difference in response achieved for real and artificial cracks as shown in terms of POD data given in Fig 9.

Central to almost all advanced ultrasonic NDT is the move to computer based systems which are either mixed analog/digital or

completely digital. This new technology has opened the door to a wide range of improved imaging, image processing, signal processing and inversion schemes. A key area in this change has been the increased capability of high speed analogue to digital conversion. For transient 20 MHz signal capture 100 or 125 MHz sampling capability is now available in several instruments. The availability of standard ultrasonic transducers which can operate at frequencies above 50 MHz has significantly improved the potential detection capability in high frequency C-scan or acoustic microscopes. Standard analogue ultrasonic instruments are now available which work up to 150 MHz.

Given computer based systems and digitised data, improvements can be made to the system signal-to-noise performance. Most techniques which improve the S:N have implications for either scan times or computer power needed or both. Increasing the power to the transducer has been shown to be able to increase signal levels by up to 12 dB. The use of focused transducers can also provide improvements in power levels by up to 6dB.

Averaging is found to improve S:N performance by several dB, for example, in theory if only random noise is present given some 10^4 cycles an improvement of 40 dB could be achieved. In practice between 3 and 6 dB reductions in noise are achieved by 64 averages; however this does depend on material properties and grain size. More complex techniques such as cross correlation and autocorrelation can be employed.

Signal processing, such as deconvolution, is also an integral part of ultrasonic spectroscopy, to remove constant background signals and reduce signals to their impulse response given the optimum filter. Dynamic averaging can be used on coarse grained materials where the transducer step is small compared with significant defect sizes and the signals are averaged in groups of three or more nearest neighbours.

Many papers have been written on signal processing for NDT; however most systems in use for precision component inspection at present appear to use simple pulse-echo measurements and A-scans. The 'A' scan responses for a series of flat bottom holes FBH) which are used as standard calibration responses are shown as Fig. 10.

Given a basic ultrasonic system an improvement of the order of 30dB in S:N can be expected to be able to be achieved through improved system design and signal processing. Over the next few years there can be expected to be increased use of digital ultrasonic instrumentation. New transducer configurations and direct computer based inversion such as Born inversion or SPOT employed. Both immersion and water jet couplant systems are being employed.

a. <u>For bulk inspection with improved transducers :</u>

Using broad band or focused high frequency ultasonics. (10 to 50 MHz) Such bulk inspections can be used to produce an image (C-scan) or individual reflected pulses can be studies and inversion schemes such as SPOT or Born inversion can be employed. The digital systems now being developed with colour graphics systems can give improved detection capability. The various inversion schemes which are being used to characterise small scatterers remains the subject of debate and further evaluation work is clearly required.

b For surface inspection two specific technologies are under consideration.

These involve ; i. the use of leaky Rayleigh waves. and ii. the acoustic microscope at about 50 Mhz. (A major part of the contrast in the acoustic microscope is due to the presence of leaky Rayleigh waves, so these technologies are related.)

Leaky Rayleigh waves generated with a compression wave transducer set at the leaky Rayleigh wave angle. The transducer is then used in a pulse-echo mode.

The acoustic microscope has been developed significantly as an industrial tool by GE in the USA (Gilmore et al (1986)) to give an instrument working mostly at 50 MHz, but can be used at almost any frequency between 10 and 100 MHZ. This system has the capability to look at complete aero-engine turbine discs.

The difference between an acoustic microscope and a normal C-scan system used near a surface can be considered to be that the C-scan looks at the compression wave signals reflected from a particular plane, whereas an acoustic microscope looks at a combination of compression and leaky Rayleigh waves generated at a surface. The compression/leaky Rayleigh wave interaction is characterised by the V(Z) curve.

Areas for possible development in ultrasonic NDT are EMATS, (Electromagnetic Acoustic Transducers) and in laser generated ultrasound which can be used to give to give non-contact inspection. Phased arrays can be used for improved scanning.

EMAT's have now been developed which can operate up to a frequency of about 5 MHz. The major problem is the generation of a very high magnetic field in a small volume and the heating due to high currents required to flow in fine wires. They are also attractive as they can generate SH, SV and Compression waves depending on the design used. They are one of the few practical ways to provide SH waves which have considerable attraction for use as an inspection wave field, not least because the mathematics used to analyse the scattering problems is much easier than for SV-C wave problems.

Laser generation of ultrasound is an area of current work. It has considerable potential for non-contact inspection. Given optical fibre technology using this form of ultrasound generation and for crack detection. Work is in progress to understand and use both the surface waves and the bulk waves generated using from laser generation of ultrasound.

There has been significant interest in the development of phased array ultrasonic systems. Most of this work has been limited to the inspection of thick steel sections in the nuclear industry. Todate many systems have operated at low frequencies and the numbers of elements in the arrays have been limited, not least because of the complexity of the electronics involved. Complex arrays are used extensively in medical ultrasonics and in the fields of Sonar and Radar and there is the potential for its application in NDT. Linear arrays and simple cylindrical arrays are being employed in medical systems, but as with nuclear inspection this tends to be at a lower frequency (≈5MHz) than that used in aero-space NDT.

Current Capability of ultrasonic NDT.

In the 1974 data given in Table 1 it was stated that a laboratory detection limit for surface cracks in steel using ultrasonics of 0.12 mm (120 μm) and a production limit of 3mm could be achieved. Using leaky Rayleigh waves at 10 MHz, cracks of 0.05 mm (50μm) can easily be detected on a good surface.

Various defect characterisation schemes such as Born and SPOT (which give type, size and orientation data) are now available for evaluation on real components. Given improvements in transducers and automated digital instrumentation production ultrasonic NDT should be capable of development, within 5 years, to give a detection capability close to a 50 μm limit for the inspection of metals with a 10 μm or less grain size.

References for ultrasonic NDT.

General references are to be found in the Quality Technology and Metals Handbook. (see references for Introduction)

Elastic wave theory:
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Graff K. (1975) Wave motion in elastic solids. Oxford.

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Krautkramer J & H (1983) Ultrasonic Testing of Materials. Springer-Verlag. (3rd English Edition)

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Gilmore R S, Tam K C, Young J D and Howard D R (1986) Acoustic microscopy from 10 to 100 MHz for industrial applications. In "Novel Techniques of NDE", Edited by E A Ash and C B Scruby The Royal Society, London. pp 55-75.

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Advanced research in:
Review of Progress in QNDE, Vols 1- 6. Edited by D O Thompson and D Chimenti. Plenum.

Proceedings; Ultrasonics International. (Biannual, '71...83,85,87)

Journals:
Ultrasonics, (Butterworth), and NDT publications.
Also IEEE, Acoustic Soc. America and IEE journals.

TYPE	REGIME	ADVANTAGES
IMAGING	ka>6.3 (λ<a)	HIGH INFORMATION CONTENT EASILY INTERPRETED DISPLAY RESOLVES MULTIPLE FLAWS
MODEL BASED RECONSTRUCTION	ka >3	PHYSICAL PRINCIPLES USED TO IMPROVE RESOLUTION AND TREAT MODE CONVERSION
MODEL BASED ADAPTIVE LEARNING NETWORKS	0.4<ka<3	MULTIPLE SCATTERING TAKEN INTO ACCOUNT GAIN MORE INFORMATION IN DIFFICULT REGIME
LONG WAVELENGTH SCATTERING	ka<0.5	FRACTURE RELATED PARAMETERS DEDUCED FROM A FEW MEASUREMENTS MAY BE USEFUL IN AUTOMATION

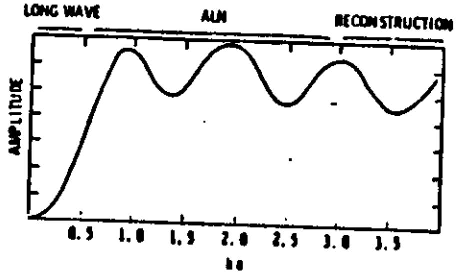


Table 7.

I. Single and Double Transducer Systems

A. Single Transducer (A,B,C, Scan; Reflection Mode)
B. Double Transducer (C Scan; Transmission Mode)

II. Multiple Transducer Systems

A. Sequenced Linear Array
B. Electronically Phased Linear Array
C. Two-Dimensional Array (NXN)

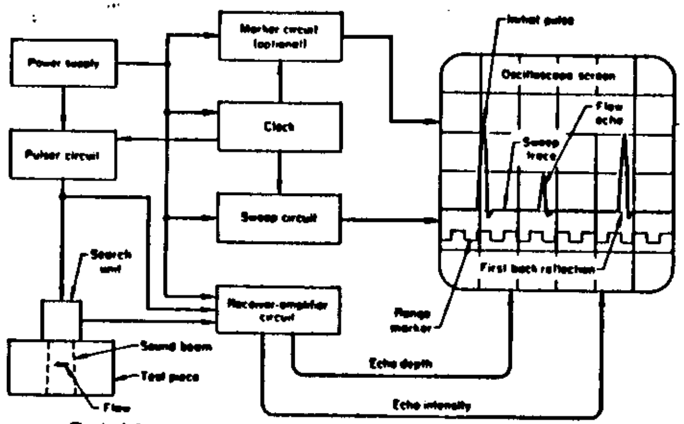
III. Systems Using Optical Diffraction or Reflection

A. Laser Illuminated Liquid-Air Interface
B. Bragg-Diffraction Imaging
C. Laser Illuminated Membrane
D. Laser Scanned Solid Surface

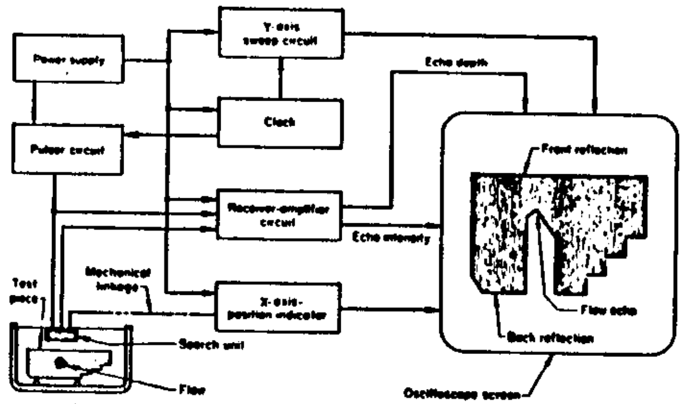
IV. Model Based Reconstruction

A. Born Approximation
B. POFFIS

Table 8. Types of Ultrasonic Imaging Techniques



Typical A-scan setup, including video-mode display, for a basic pulse-echo ultrasonic-inspection system



Typical B-scan setup, including video-mode display, for a basic pulse-echo ultrasonic-inspection system

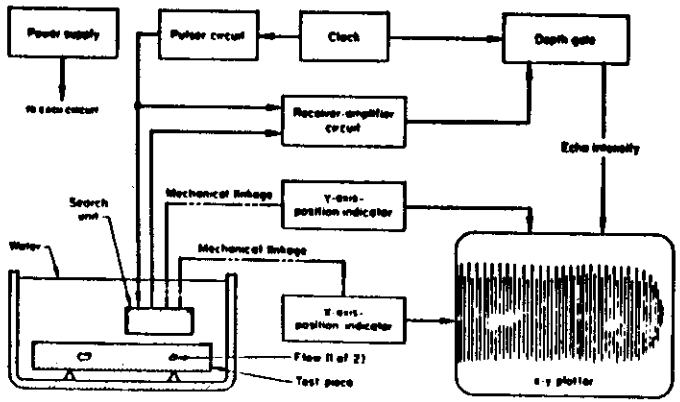


Fig. 4. *Typical C-scan setup, including display, for a basic pulse-echo ultrasonic-inspection system*

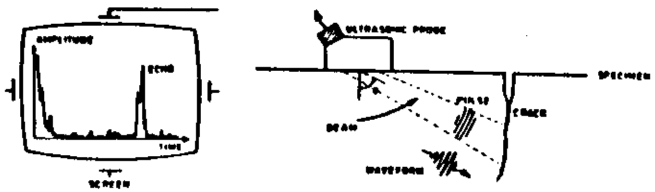


FIG. 5

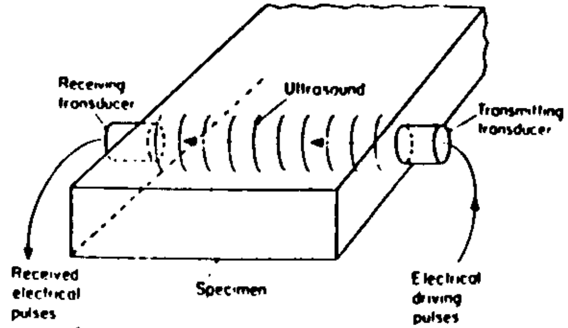


Figure 6 *The transmission inspection method*

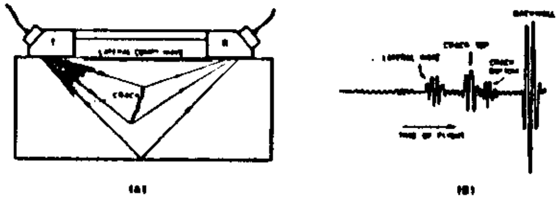
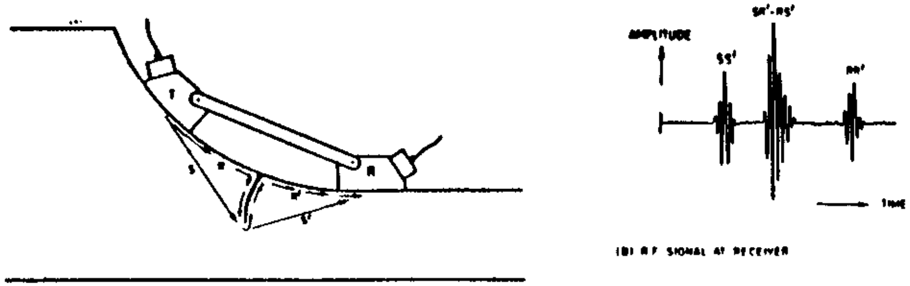
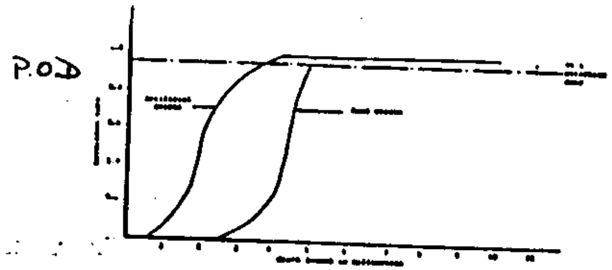


FIG. 7 *Harwell time of flight system for embedded cracks.*

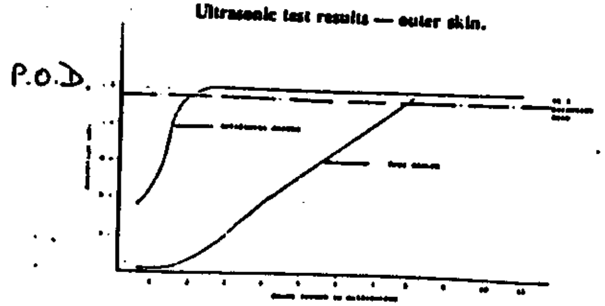


(A) RAYLEIGH AND SHEAR WAVES INTERACTING WITH CURVED CRACK

(B) R.F. SIGNAL AT RECEIVER



Ultrasonic test results — outer skin.



Ultrasonic test results — inner skin.

Figure 9

Relative Amplitudes for 1/64", 2/64" & 3/64" F.B.H. Targets Set to the same Sensitivity.

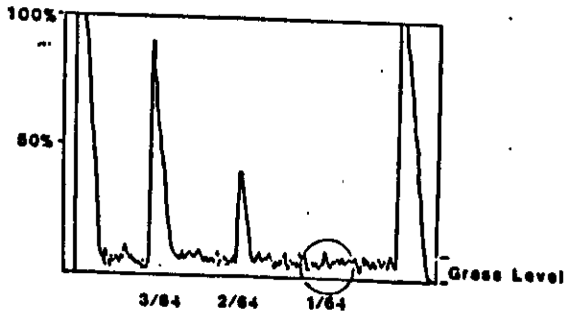


Figure 10

Acoustic Emission.

This technique is in many cases called a non-destructive testing or condition monitoring tool. However it is not a true NDT technique as it is based on the detection of the stress waves generated when a crack grows!!

It was reported by Brunel over 150 years ago that acoustic emission in wooden roof boards was used by tunnel workers to give the best indication of increasing load. Acoustic emission in metals developed from studies in the 1930's and '40's. The initial work considered frequencies in the range 150 to 10,000 Hz. Work by Kaiser in 1950 is considered to be the first serious work inthe field of AE applied to metals. recent work has in many cases concentrated on developing techniques to monitor pressure vessels. The frequencies of interest tend to be above the audio band and below the conventional ultrasonic NDT frequencies.

The physics of the waves encountered in AE are the same as for ultrasonics. An acoustic emission is like a mini-earthquake and it is a small line or pseudo-point source.

A set of transducers with a wide-band frequency response are used (usually three or four) and the arrival times of stress waves from the emission are recorded, the source can then be located by triangulation. The concept was very popular about 10 years ago and it was a technology that was oversold. It is now being reconsidered as the science base has developed. It has its uses but must be considered with care. Some material is quiet and gives few or weak AE events when a crack is growing! It is difficult to interpret and quantify either the source or the effect of a complex geometry on the waves. In some cases the signal to noise for AE events is poor and background mechanical noise can make positive detection difficult. For good detection and location AE events should be inside the receiver pattern.

Various forms of Acoustic Pulsing which are an active ultrasonic system are being used to fingerprint structures. This remains an area of current research.

References.

Matthews J R, (Editor) (1983) Acoustic Emission. NDT Monograph, Vol 2. Gordon and Breach Science Publishers.

The development and current practice of AE is considered in;

Dukes, R and Culpan E A. (1984) Acoustic Emission: its techniques and applications. IEE Proceedings Vol 131 Pt A No 4 June. pp 241-251. (63 references)

Eddy current and other Electromagnetic NDT technologies..

Eddy current inspection is based on electromagnetic induction. It can be used to measure electrical properties, detect seams, laps cracks etc, to sort dissimilar metals and to measure coating thickness. It is a non-contact technology which monitors surface and near surface partameters.

Eddy current NDT combines electromagnetic induction, the theory and application of induction coils, the solution of boundary value problems to describe the fields, sensitive instrumentation for detection, display, data recording and metallurgy.

Electromagnetic induction was discovered by Faraday in 1831. Maxwell in 1864 presented his classical dissertation on the electromagnetic field. In 1879 Hughes used eddy currents to detect differences in electrical conductivity, magnetic permeability and temperature in metal.

An eddy current instrument for measuring wall thickness was developed by Kranz in the mid-1920's. By 1935 Farrow had developed an inspection system for welded steel tubing. The inspection frequencies were 500, 1000 and 4000 Hz. By 1935 the small drilled hole was introduced as a calibration standard. In the early 1940's Forster and Zuschlag developed eddy current inspection instruments.

A block diagram showing eddy current generation in a tube or rod is shown as Fig 11. It is changes in the coil-sample impedance which are sensed. Four types of eddy current instrument are shown in Fig.12. It is the interaction of the induced eddy currents with the sample under examination which is the basis of this type of NDT. A search coil over a plate is shown in schematic form as Fig 13. The impedance plane diagram for the system shown in Fig 13 is shown as Fig 14. The change in impedance seen between points A and B can be caused by several factors which are considered below.

The equivalent circuit for the eddy current/sample system and phasor representation is considered further in Figsâs 15 and 16.

Two types of eddy current coil arrangement are shown as Fig 17. When a search coil of the type shown in Fig 13 is used near various types of defects the effects of various types of features are shown as Fig 16. A range of eddy current coil configurations for use in specific geometries have been developed and the probability of detection achieved is shown as Fig 19.

The science base for the quantitative understanding of eddy current defect interaction is weak. Theory based on analytical solutions is limited to symmetric geometries and non-magnetic (linear) isotropic media with coils made from a single loop. A summary of much of the available theory has been provided by Tegopoulos and Kriezis (1985).

When real complex coils and real 3-D component and defect geometries are considered analytical solutions are not yet available (the maths is hard or very hard) and numerical models based on finite element methods are now being employed.

For simple configurations which are mostly in 2-D and involve cylindrical systems it is possible to predict the impedance for the system. Data from eddy current inspections is usually shown as an impedance plane diagram.

The basic electrical properties are the electrical conductivity and the magnetic permeability. In inspection systems the 'lift-off' or coil sample separation is a key variable; this parameter also changes the coil-sample impedance. The effect of changes in various parameters on the impedance plane display is shown as Fig 18.

It is however found that at a particular frequency it is the eddy current skin depth and the probe characteristics, in particular those of the ferite core material and the ratios of these parameters with defect dimensions that in general determines detection capability.

The basic skin depth for an eddy current in a material is calculated using the equation;

$$\delta = (\pi f \mu \sigma)^{-1/2}$$

where μ permeability = (B/H)
σ conductivity.
B flux density.
H magnetic field strength.
f frequency of exciting field.

The two parameters which characterise response are then;

D/δ, where D is the defect size, usually its depth ,
and l/d, where l is the surface breaking length and d is the probe diameter.

The two major variables in an NDT system then become the type of coil (absolute or differential) and the operating frequency. To ensure good detection defects are required to be of the same order or greater than the skin depth. features deeper than 1.5 skin depths will not be detected.

To extract more data from eddy current inspection multifrequency systems are now being used. Also some work is in progress to use data collected as a part is scanned. However much work remains to be done if an adequate science base for eddy current defect interactions is to be developed and more quantitative analysis provided.

Practical eddy current NDT at present tends to rest on the use of test blocks with calibration features.Todate little has been done to extract more quantitative sizing data from the conventional eddy current impedance plane displays. Multifrequency instruments have been introduced and eddy current arrays are being investigated. However most systems still use a relative rather than quantitative sizing techniques.

Further significant improvements in the fundamental science base for eddy current defect interaction can be expected within 5 to 10 years. Progress is being made by several groups. The complete analytical solutions for many probe-field-defect interactions cannot be expected, but numerical models and approximate theories are being developed, although progress does remain slow. It is an area where the problems are hard, as systems involve 3-D field problems.

Major progress has been made in terms of detection capability using small ferrite cored probes. In the USA the YIG sphere has been developed as a sensor at Stanford University and this is under evaluation by GE, with USAF support.

As with ultrasonics, advanced analog and digital eddy current NDT systems are under development. Also automated scanning has already significantly improved the detection capability that has been achieved on real components. Multifrequency instruments can be expected to be developed further. New forms of data treatment, eddy current inversion and data display are all under consideration. At present the major problem is the lack of adequate forward models for the field-defect interactions.

Eddy current systems which employ the Nortec 33 are part of the Kelly USAF base RFC inspection system. Also as part of this program a range of small probes are being developed and evaluated. For eddy current inspection the probe design is a crucial element.

Capability of eddy current NDT.

Eddy currents have been demonstrated to have a good capability for defect detection using automated linear probe scanners for disc and blade fir tree regions and rotating probes for use in bore holes. This capability has been quantified as was shown in Fig 17.

Eddy current NDT can in many geometries be expected to detect defects with a high reliability down to crack depths smaller than 0.010 inch (≈ 0.24 mm) and in some cases to half this figure.

Two new electromagnetic NDT systems are now available. The first system is made by PN Industries and itis designed for turbine disc inspection. The system uses Nortec eddy current equipment, and Intelledex Robot and DBC computers. Few details have been released but its specification states that it inspect discs with a maximum diameter of 1200 mm and with a thickness of 500 mm. The claimed inspection capability is detection down to 0.8 mm (800 μm) surface length .

The second system uses Electric Current Perturbation methods and it has been developed by Southwest Research Institute for use on non-magnetic super alloys and evaluated on the F-100 engine discs. The ECP system can be used to scan a wide range of disc regions. Traces have been shown with indications from notches down to 0.22 x 0.05 mm. Good signal to noise is being given for defects of 0.47 x 0.17 mm.

In the data given in Table 1 the eddy current laboratory limit was given as 0.25 mm (250 μm) and the production limit was given as 2.5 mm. A crucial element in determination of the detection limit is combination of surface state, probe design and its frequency, and both the material properties and their geometry.

References.

Quality Technology and Metals Handbooks. (see Introduction)

The available analytical theory for some eddy current problems is given by;

Tegopoulos J A and Kriezis E E (1985) Eddy currents in linear conducting media. Studies in Electrical and Electronic Engineering, Vol 16 Elsevier.

The theory for eddy currents has been reviewed by;

Auld B A, Muennemann F G and Riaziat M (1984) Quantiative modelling of flaw responses in eddy current testing. Research Techniques in NDT, Vol 7, Ed. R S Sharpe. Academic Press.

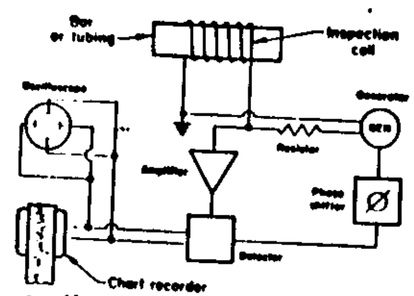


Fig. 11. Principal elements of a typical system for eddy-current inspection of bar or tubing.

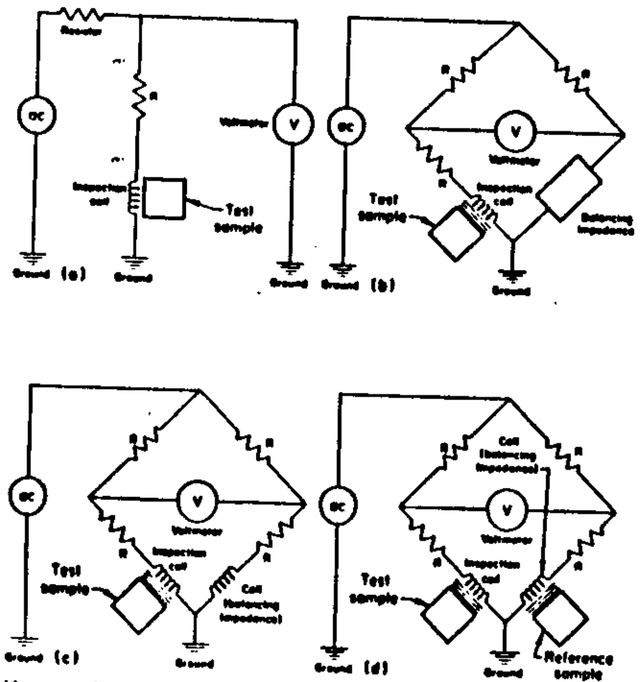


Fig. 12. Four types of eddy-current instruments: (a) a simple arrangement, in which voltage across the coil is monitored; (b) typical impedance bridge; (c) impedance bridge with dual coils; and (d) impedance bridge with dual coils and a reference sample in the second coil

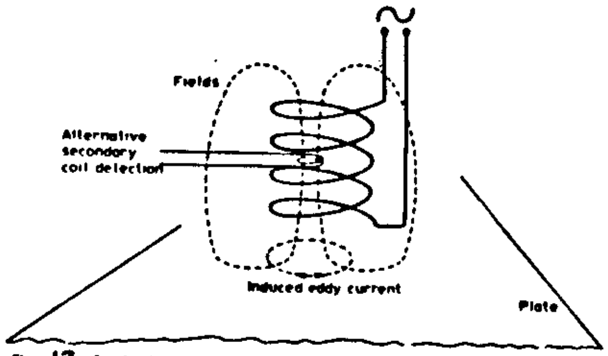


Figure 13. Search coil eddy-current test

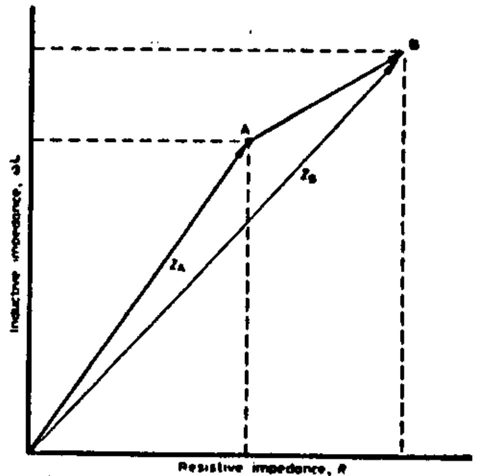


Figure 14. Impedance plane diagram demonstrating amplitude and phase-change experienced in eddy-current testing. Impedance, Z, of test coil

$$Z = \sqrt{(\omega L)^2 + R^2}$$

A, initial condition. B, condition due to change in specimen

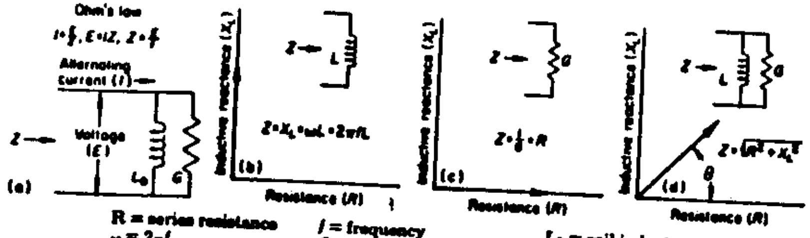


Fig.15 (a) A simplified equivalent circuit of an eddy-current inspection coil and part being inspected. (b), (c) and (d) Three impedance diagrams for three conditions of the equivalent circuit.

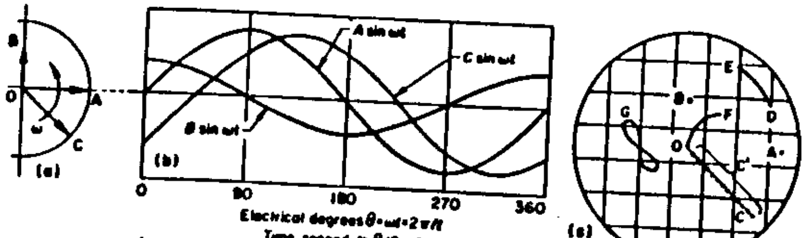


Fig.16 Phasor representation of sinusoids.

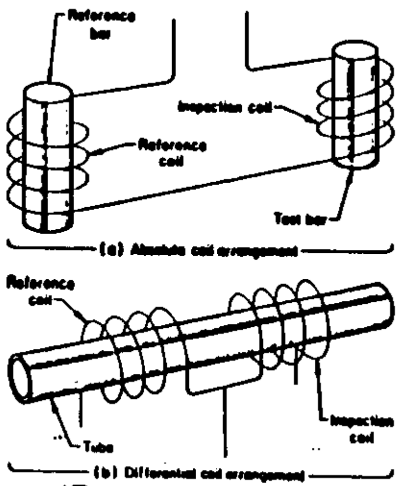


Fig.17 Absolute and differential arrangements of multiple coils used in eddy-current inspection.

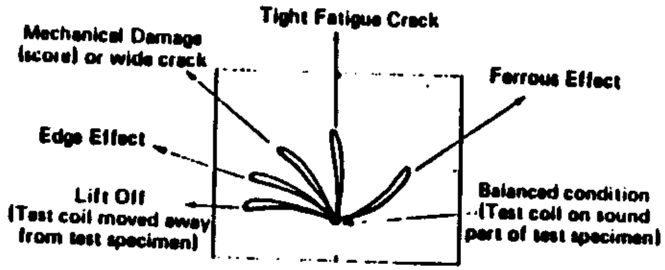


Fig. 18

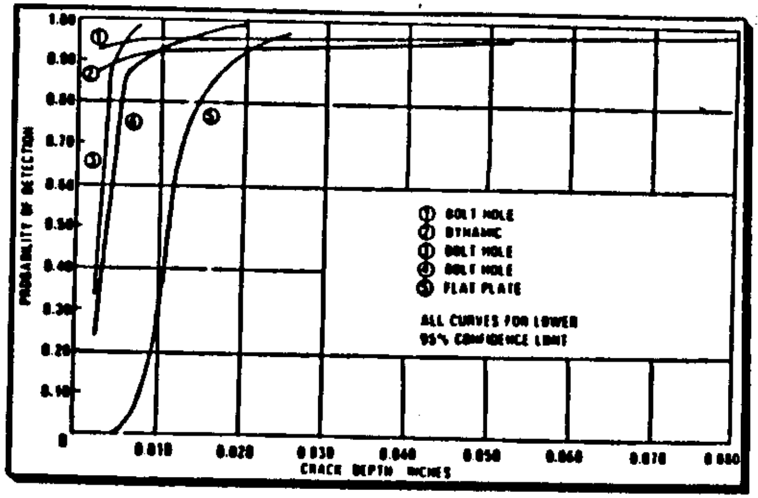


Figure 19 - Probability of Detection - Eddy Current

Potential Drop Techniques.

In addition to conventional eddy current NDT there are various potential drop techniques; DC PD and AC PD. Significant progress has been made in the application of ACPD or ACFM to offshore structures. (Dover et al (1986)). The theory involved in field-defect interaction is simpler than for conventional eddy currents.

When an electric current passes through a metal sample there is a drop in potential with distance which depends on the sample resistance.

Ohms law; V=I/R; V volts, I current and R resistance

The measurement of this drop in the potential with distance forms the basis for the potential drop inspection techniques.

In this course only one form of potential drop is mentioned and this is ACPD or AC field measurement.

The AC field is induced in a sample and the potential measured between two contacts. When the measurement head is positioned over a crack, which is deep compared with the skin depth, the change in potential is proportional to twice the crack depth. The ACFM technique is shown in schematic form as Fig.20.

For the electromagnetic inspection technique known as ACFM two families approximate theory solutions are available for field-defect interaction and these correspond to thick and thin skin approximations both defined in terms of the D/δ ratio. For ACFM the theory is simpler than for eddy currents as the problems in general reduce to calculation of the potentials in a surface skin and hence only involve two space dimensions. (Dover et al (1986)

It is a technique which has been extensively developed to monitor crack growth in fatigue studies. Point contacts are required to measure the potential on the part.

References,

Collins, R, Dover W D and Michael (1985) The use of AC field measurements for NDT. In "Research Techniques in NDT, Vol 8" Edited by R S Sharpe, Academic Press.

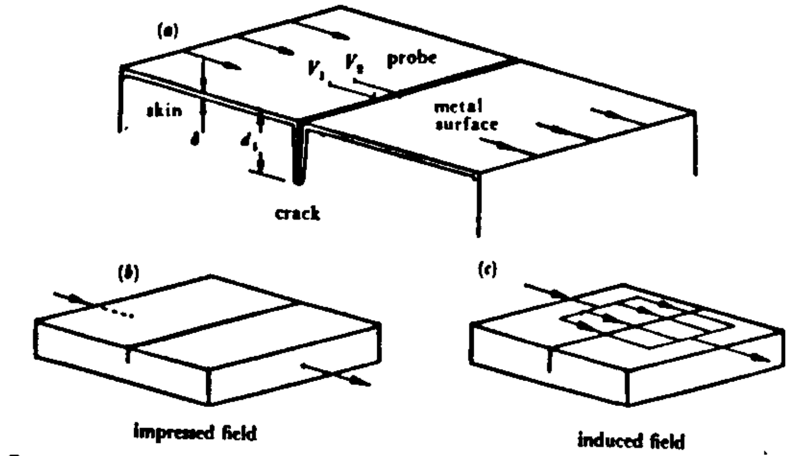


FIGURE 1. Measurements required for crack depth prediction in a uniform AC field distribution.

$$V_1/\Delta = V_2/(\Delta + 2d_1)$$

so that

$$d_1 = (\tfrac{1}{2}\Delta)(V_2/V_1 - 1).$$

Radiography.

Radiography in all its various forms is probably the most commonly used NDT technology. It provides a record of the inspection and an image of any defect. In particular when used on site and when gamma sources are employed there are major health and safety questions which require careful attention to detail. Also radiography has limitations on the types of defects that it is most suited to detect; e.g. tight fatigue cracks can be missed unless exposures are performed from several directions.

The use of X-rays for NDT was suggested soon after they were discovered in 1895, but the short wavelengths needed did not become available until about 1919. The fundamental aspects of X and gamma - radiography are well established.

The current range of types of radiography use; x-rays, gamma rays and neutrons.

The fundamental aspects of the interaction of radiation with matter are used in several types of systems. Two basic classes of x-radiography are performed and these are; 1. radiography where a film or sensor is used and fluoroscopy where a screen and direct or TV viewing is employed. The variable factors in radiography are shown as Fig 21.

In recent years the technology used to implement radiography has been developed to give; Real time.,and Micro-focus. systems. A standard X-ray tube system is shown as Fig 22.

The most important parameter which can be used to characterise a radiography system is its spot size. This is determined by the wavelength for the radiation given at a particular energy and the geometry of the x-ray tube and detector employed. Spot size down to 0.5 mm and now much less are being achieved.

Various data which characterises x-ray systems is given as Figs 23 and 24. Figure 23 shows the relationship between power rating and focal spot diameters. The relationship between wavelength and relative intensity is shown as Fig 24. It is then the detector geometry and the sensitivity of the film/ detector employed, given the number of photons received which determines detection and resolution limits and the sensitivity. To reduce exposure time and improve imaging capability for thick metal sections gamma radiography is used. The energy spectra for three gamma emitting isotopes is shown as Fig 24.

Basic radiographic equations

(1) ***Absorption.*** The intensity of a collimated beam of energetic emergent X- or gamma-rays having passed through a solid (ignoring scatter) is given by

$$I = I_0 e^{-\mu t}$$

where I is the intensity of the emergent rays, I_0 is the intensity of the incident rays, μ is the linear absorption coefficient for the material (at the particular wavelength of radiation used), t is the thickness of the material, and $e = 2.718$.

The relationship between linear and mass absorption coefficients of a particular material is given by

$$\mu = \mu_m \rho$$

where μ is the linear absorption coefficient, μ_m is the mass absorption coefficient, and ρ is the density.

(2) ***Half-value thickness.*** The hardness or penetrability of an X- or gamma-ray beam is often expressed in terms of the thickness of a particular absorber which will absorb half of the incident radiation; this is known as the half-value layer (HVL) for the material and is given by the expression

$$\mathrm{HVL} = \frac{0.693}{\mu_{\mathrm{HVL}}}$$

where μ_{HVL} is the linear absorption coefficient for a practical continuous-energy X-ray beam spectrum

(3) ***Inverse square law.*** The intensity of a beam of radiation falls-off as the square of the distance from the source. Expressed in terms of exposure

$$\frac{\text{Exposure required at distance } d_1}{\text{Exposure required at distance } d_2} = \frac{d_1^2}{d_2^2}$$

(4) ***Limiting wavelength of X-rays.*** This is defined by the expression

$$\lambda_{min} = \frac{12.35}{V}$$

where λ_{min} is the minimum wavelength of the emitted radiation and V is the maximum operating voltage of the X-ray tube, expressed in kilovolts.

(5) ***Build-up factor.*** This is a factor which describes that amount of radiation scattered from the X-ray beam which falls on to the film, but which does not contribute to the formation of the true radiographic image. The factor, B, is given by the expression

$$B = 1 + \frac{I_s}{I_d}$$

where I_s is the intensity of the scattered X-rays and I_d is the intensity of the direct image-forming X-rays.

(6) ***Film density D.*** This is given by the expression

$$D = \log_{10} \frac{I_0}{I_t}$$

where I_0 is the intensity of the light incident on the film being examined and I_t is the source, is given by

$$U_{max} = \frac{tD}{F - t}$$

where t is the specimen thickness. For good quality gamma radiographic work it is generally accepted that U should not be more than 0.25 mm.

intensity of the light transmitted through the film at any particular point. For example, a film density of 2 implies a light transmission of 1 per cent.

(7) *IQI sensitivity.* This is given by the expression

$$\text{Sensitivity (\%)} = \frac{\text{Thickness of smallest detectable IQI element}}{\text{Thickness of specimen}} \times 100$$

(8) *Radiographic exposure* (E). This is given by

$$E = It^{p}$$

where I is the intensity of X-ray beam, t is the exposure time, and p is Schwarzschild's constant (1.0 for direct X-rays and approximately 0.8 when salt screens are used). A number of factors affects radiographic exposure, which can be expressed as

$$E = \frac{d^2 F}{A(V)^n}$$

where d is the object-film distance; F is a factor incluenced by the sample characteristics, filtration of beam and generator characteristics; A is the X-ray beam current (milliamperage); V is the generator kilovoltage; and n is the power value dependent on kilovoltage range.

(9) *Thickness sensitivity, S.* This is given by

$$S = \frac{\Delta x}{x} \times 100 = \frac{2.3 \Delta D}{\mu G_D x}\left[1 + \frac{I_s}{I_D}\right] \times 100$$

where S is the precentage thickness sensitivity (e.g. a code might call for 1 per cent sensitivity). Δx is the minimum thickness-change which can be discerned on the radiograph, x is the sample thickness, ΔD is the minimum discernible density difference detectable by eye (usually between 0.006 and 0.01, depending on the film viewing conditions), μ is the narrow-beam linear absorption coefficient, G_D is the film gradient [$d(D)/d(\log E)$] *at the film density used*, I_s/I_D is the ratio of scattered/direct radiation intensities reaching the film at the point being considered, and $[1 + (I_s/I_D)]$ is the 'build-up' factor.

(10) *Intensification factor for intensifying screens.*

$$I_D = \frac{E_{0D}}{E_{SD}}$$

where I_D is the intensification factor at film density D, E_{0D} is the exposure required to produce density D with no screens, and E_{SD} is the exposure required to produce density D with the screens.

(11) *Geometric image formation.* The relationship between the size of the source and image sharpness (*see Figure*) is given by

$$U_G = \frac{aD}{F - a}$$

where U_G is the geometric image unsharpness, D is the diameter of source, F is the distance from source to film, and a is the distance from flaw to film. The maximum unsharpness, which arises when the flaw is at the surface of the test piece nearest to the

(12) *Radioisotope decay.* The exponential decay rate of a gamma-ray isotope source is usually expressed in terms of a half-life, which is the time after which the strength is reduced to half of its original value.

$$C_R = C_0 e^{-0.693t/H}$$

where C_0 is the initial strength, C_R is the strength after time t, and H is the half-life value for the isotope.

If the focal spot for the system is used to define an image pixel then the use of projection radiography can further improve performance in terms of resolution and also increase the radiographic contrast. However some types of defects such as tight fatigue cracks at least in some orientations may not be detected using conventional radiography.

When production inspection is considered inspection time, limits on radiation levels and part geometry will all limit performance. As with conventional photograpby poor technique can generate poor images with 'Spurious' indications, a list of some sources of such indications is given as Table 9.

The most interesting areas for development are micro-focus radiography and CT scanning. A CT system is shown in schematic form as Fig 25.

Forward models for simulated radiographs have been developed in some fields and CT-computed tomography system modelling is now being developed.

-..-

Capability of Radiography.

There have been very considerable advances in radiography in recent years. Much work has been performed in the medical field and there is technology which could be applied to NDT problems.

Two areas where there have been particular developments are in microfocus X-ray and computed Tomography (CT). This is now being developed for limited sector scanning which has considerable potential.

The use of microfocus techniques has reduced the spot size and projection radiography combined with new thin solid state detectors has improved system resolution when compared with the data given in Table 5. A key factor in determination is orienation of defect and source. When the capability of X-radiography is evaluated POD data of the form shown as Fig 26 may be obtained. Fatigue cracks are hard to detect.

It is to be expected that within 10 years CT systems will be used for the routine inspection of critical high quality components. Real time radiography, and digital radiography based on solid state detectors can be expected to be developed further. A major factor which may limit their use in NDT is the initial capital cost of a system.

When a CT system is used there can be solid state detector widths down to 4 thou which can give 25 micron spatial resolution. The detection capability for density change is 0.02% This figure was obtained for CT on a hemisphere of plastic about 6" in diameter. This data can be compared with defect detection limits in steel of 0.5 mm given in Table 1.

References.

Quality Technology and Metals Handbooks. (See Introduction)

There are various texts on industrial radiography;

Halmshaw R (1971) Industrial Radiography Techniques, Wykeham Publications, London.

In radiography the images are in many cases compared with standard radiographs;

Table 9 Spurious 'images' on radiographs due to faulty technique

Appearance on radiograph	*Probable cause*	*Remarks*
General fog giving an apparent lowering of contrast	Over-development. Use of badly stored film. Defective safelight. Old film	Development should be strictly to film manufacturer's recommendations for time and temperature. Safelight may have lamp of too high wattage
Finely mottled fog	Old film	Check date on film issue
Dark spots or areas, sometimes with marble-like effect	Insufficient fixation	Fix for not less than twice time required to clear. Check exhaustion of fixing solution
Random streaks or splashes	Water deposited on film after processing	Water shaken from film clip on to partly dry film is a frequent cause
Light circular or drop shaped patches	Splashes of water or fixer on film prior to development	It is possible to confuse either with weld defects
Dark circular or drop shaped patches	Developer splashes on film before total immersion in developer	This blemish may be confused with porosity
Dark areas, usually crescent-shaped	Pressure marks due to faulty handling of film after exposure	Most film emulsions are very pressure-sensitive and they should be handled by edges only
Light areas, usually crescent-shaped	Pressure marks due to faulty handling of film before exposure	Most film emulsions are very pressure-sensitive and they should be handled by edges only
Sharply outlined light or dark areas	Non-uniform flow of developer over film	Immerse film smoothly into developer and agitate film during development
Dark lines or cracks	Scratches on film emulsion or on lead intensifying screens	Examine screens and renew if necessary. Defect may be confused with cracks in object being radiographed
Dark branched lines or dark spots	Static electrical discharges on surface of undeveloped film	Rubbing or sliding one film over another, or drawing film quickly from wrapping paper may cause this fault. It is possible to confuse this defect with cracks in object being radiographed
Dark finger print markings	Film touched before development with chemically contaminated fingers	Handle film by edges only with clean, dry hands and keep film protected as long as possible. A partial, indistinct finger print can be very misleading
Light finger print markings	Film touched before development with greasy fingers resulting in restricted development	
Random markings	Dust, tobacco ash, dandruff, loose hairs, etc on film or screens	These blemishes may lead to considerable confusion when interpreting radiographs

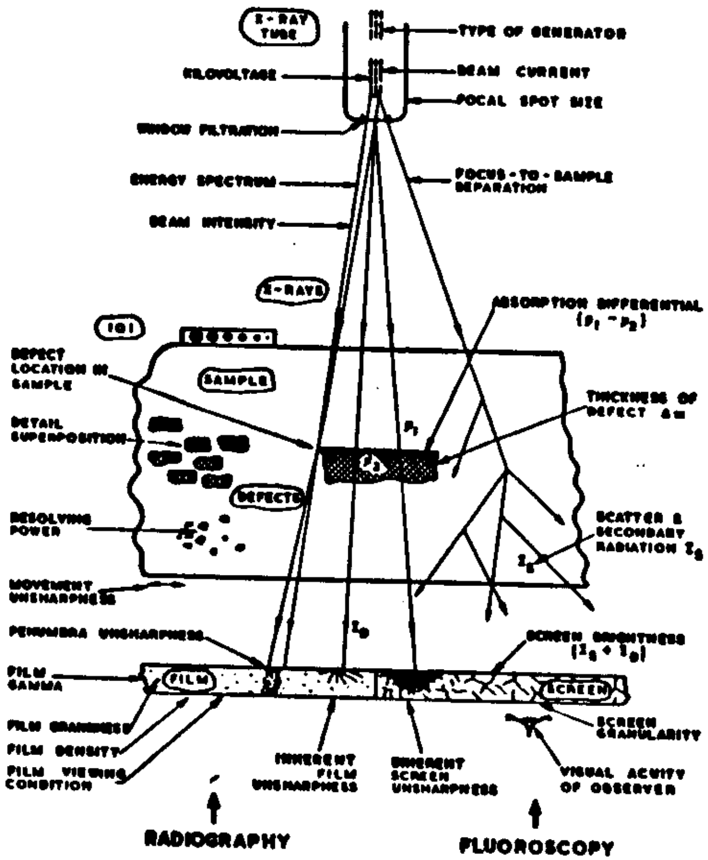
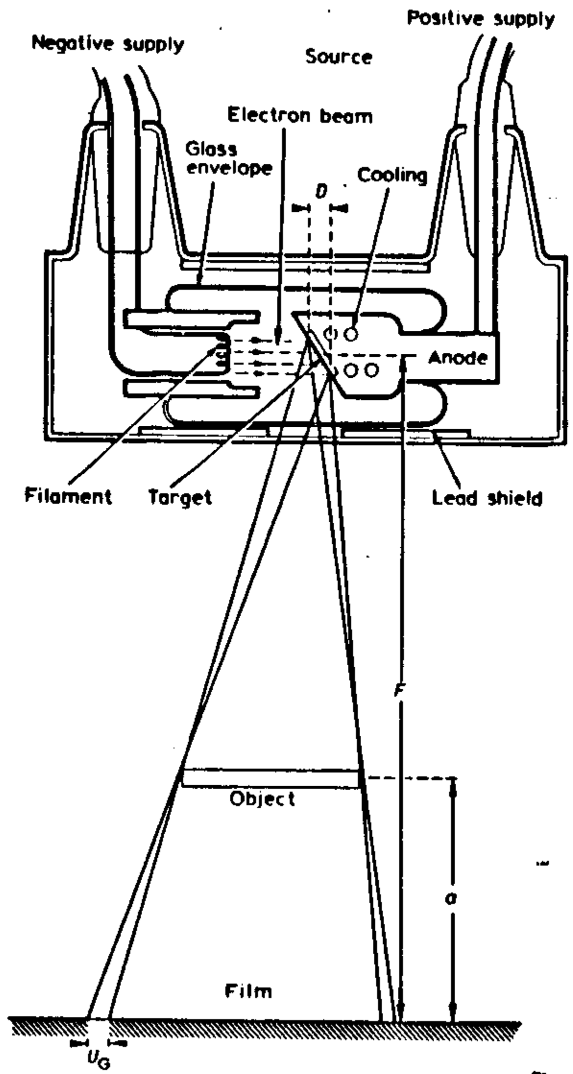


FIG.21 VARIABLE FACTORS IN RADIOGRAPHY & FLUOROSCOPY.



Geometric unsharpness, $U_G = \frac{aD}{F-a}$

Figure 2.2 Standard X8 ray tube and demonstration of geometric unsharpness

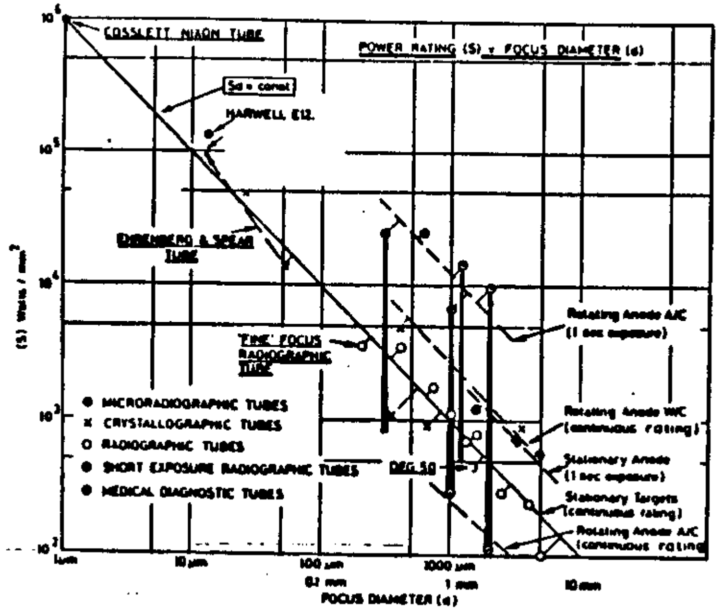


Figure 23.

Relative power ratings to focal spot diameters for various types of X-ray tube.

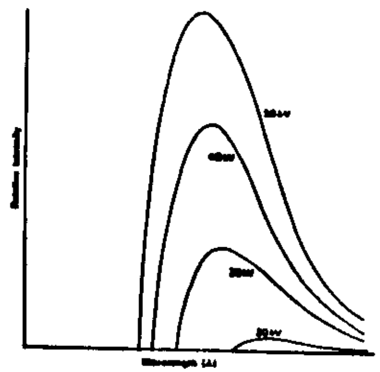


Figure 24

Illustrating the continuous spectrum of X-rays and the distribution of intensity with wavelength for differing x-ray tube voltages

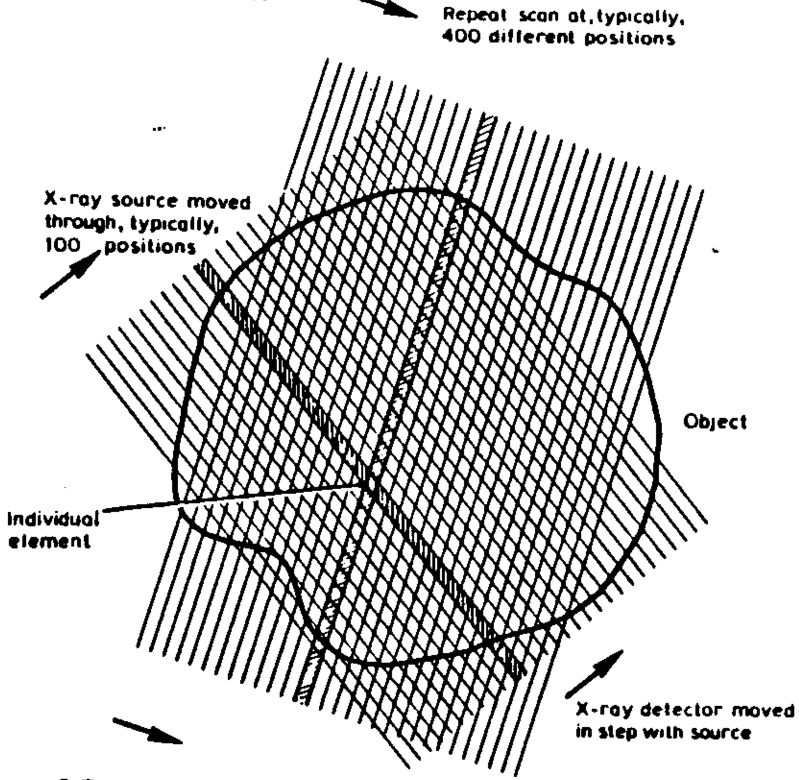


Figure 25 Computer tomography. Each element of a slice through the object will be scanned as many times as scans are repeated. By a process of iteration, the attenuation of each element can be computed and an attenuation map formed of the slice

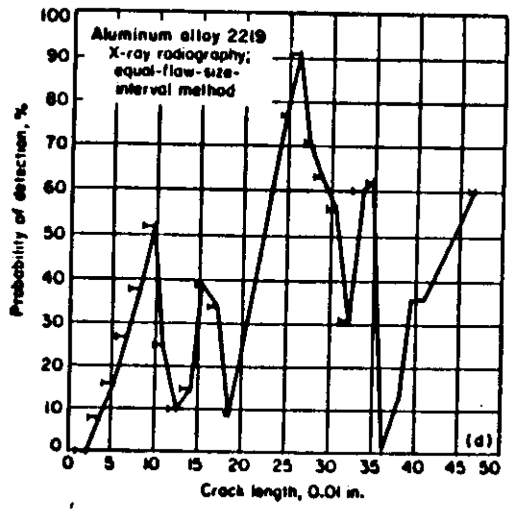


Fig.26 Charts of lower-bound probability of detection of fatigue cracks of various lengths

Reference radiographs

Sets of reference radiographs which show the appearance of weld and casting defects of different degrees of severity through different metal thicknesses are commercially available and listed below. These are particularly valuable for instruction purposes and are used by some organizations as acceptance standards.

ASTM E.99	Reference radiographs for steel welds, USA (1963)
ASTM E.155	Reference radiographs for inspection of aluminium and magnesium castings, USA (1979)
ASTM E.186	Tentative reference radiographs for heavy walled (2-4½ in) steel castings, USA (1974)
ASTM E.192	Standard reference radiographs of investment steel castings for aerospace applications, USA (1975)
ASTM E.242	Tentative reference radiography for appearance of radiographic images as certain parameters are changed, USA (1974)
ASTM E.272	Tentative reference radiographs for high strength Cu-base and Ni-Cu alloy castings, USA (1975)
ASTM E.280	Tentative reference radiographs for heavy walled (4½-12 in) steel castings, USA (1975)
ASTM E.310	Tentative reference radiographs for tin-bronze castings, USA (1969)
MIL-STD-779	Reference radiographs for steel fusion welds 0.03-5.0 in, USA (1968)
	Collection of reference radiographs of welds in steel (with three supplements), IIW (1962)
	Collection of reference radiographs of welds in aluminium and aluminium alloys, IIW (1963)

Basic NDT techniques.

Liquid Penetrant Inspection.

Liquid penetrant inspection is one of the most common forms of NDT. It can also be simple and cheap to use. This family of inspection techniques can be considered in two groups;
i. dye penetrants and ii. fluorescent penetrants.

This group of inspection techniques can only detect surface breaking cracks or other voids. Any feature that will not let the liquid penetrate will not be detected.

The physical principles are based on the wetting characteristics of particular liquids. A fluid is required which has the ability to wet the material to be inspected and it also has a low surface tension so that it will flow. The basic characterists for wetting charactristics are shown in Fig 27. The key properties of the penetrants are therefore low viscosities and their ability to penetrate into open fine cracks. The second aspect of the technology is that sufficient penetrant must remain in a fine small crack, after cleaning and developing to give either a dye or a fluorescent indication which can be easily (?) detected by either an inspector or an automated inspection system.

It is interesting to note that the data given in Table 1 gives penetrant as the technology which provides the lowest ' detection limit', at 1.25 mm, when used for inservice inspection.

The five essential operations for penetrant inspection using water-washable material are shown in Fig 28. There are corresponding sequence of operations for other types of penetrants such as the post-emulsifiable penetrant,and the process flow diagram for water washable liquid penetrant is shown as Fig 29.

The final stage in each inspection is the actual inspection; depending on the agents used either a dye will be seen in daylight or viewing under UV light in a dark room may be required.

For these groups of substances and their related cleaners, removers, developers and contrast agents the fundamental properties as well as their analysis is based in the field of physical chemistry.

There is no simple parameter which can be used to measure performance which corresponds to the ultrasonic D/λ ratio or the eddy current skin depth δ which can be used as a measure of expected detection capability.

The performance of penetrant NDT has been evaluated in several studies. However it has been found that it can be unreliable. Examples of the POD data colleced for penetrant inspection are shown as Fig 30. A major study be the USAF achieved POD data with fluorescent penetrant inspection is shown in Fig.31 To improve penetrant performance repeat independent inspections can be used, but this does increase inspection time. The degree to which the reliability of inspection can be improved is shown in Fig.32.

The major problems which limit performance have been associated with the human factors involved in viewing each individual component in a dark room and the variability with which the technology is implemented; which is in part due to variable component and defect parameters and in part due to human factors. The large uncertainty in the USAF POD (Fig 31) is felt to be due to this human factor. It has been shown that the best improvements in POD are achieved through the use of several independent inspections.

In aero-space NDT automated turbine blade viewing penetrant systems are being developed. Work has been performed by Rolls Royce to give a system which uses laser scanning to detect remaining penetrant. Similar work is in progress for the USAF. Only limited data has been found which quantifies the performance of the current automated and semi-automated penetrant inspection. This technology can be expected to remain in common use for large area inspection; the current best practice must become the norm. In the course of the next few years the various completely automated penetrant systems can be expected to be in operation and evaluated.

It has been predicted that the detection of surface cracks, inclusions and large grains in forged and cast materials will within the next 5 to 10 years be performed by automatic systems that will replace humans used for surface inspection in dye penetrant inspection.

References.

Quality Technology and Metals Handbooks (See Introduction)

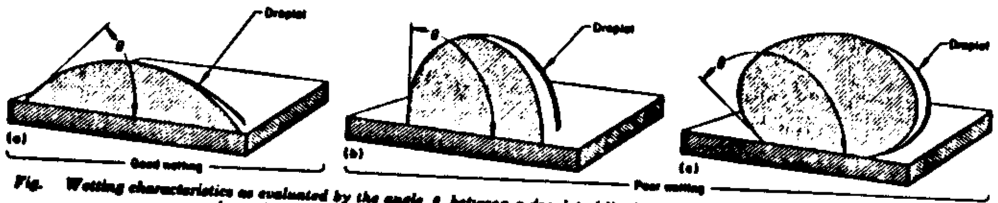


Fig. Wetting characteristics as evaluated by the angle, θ, between a droplet of liquid and a solid surface. Good wetting is obtained when θ is less than 90° (a); poor wetting, when θ is 90° or greater (b) and (c).

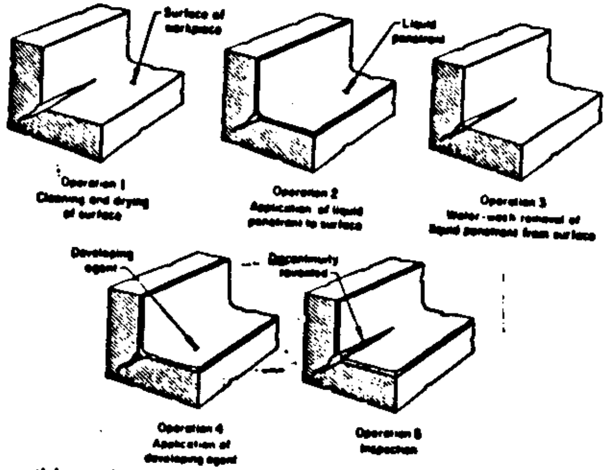


Fig. , Five essential operations for liquid-penetrant inspection using the water-washable system

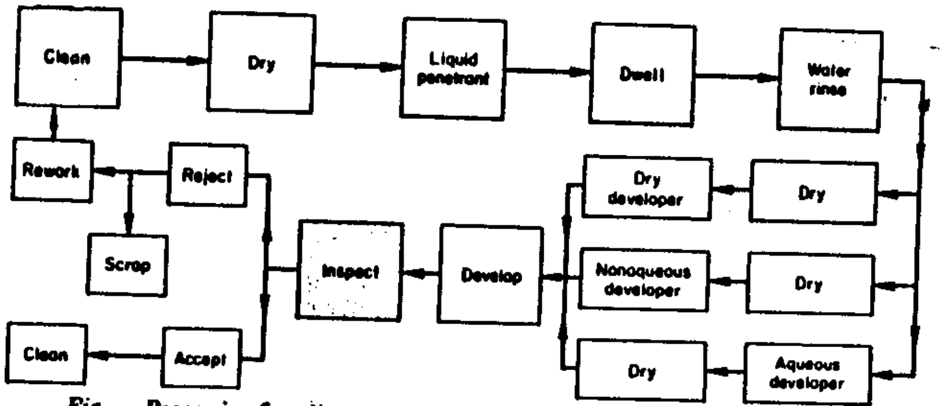


Fig. Processing flow diagram for the water-washable liquid-penetrant system

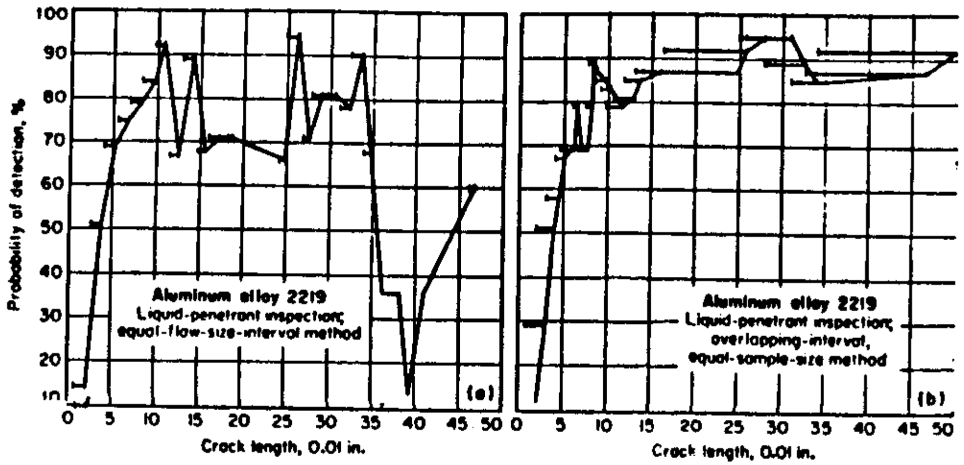


Fig 30. POD. Data for Penetrant Inspection.

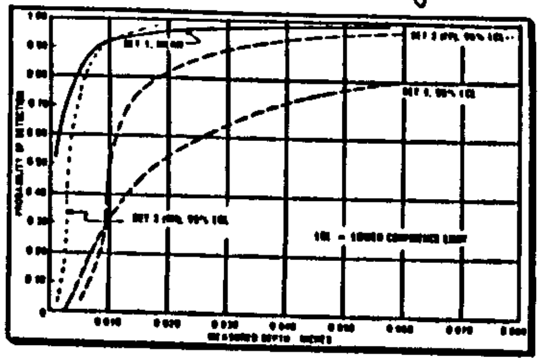
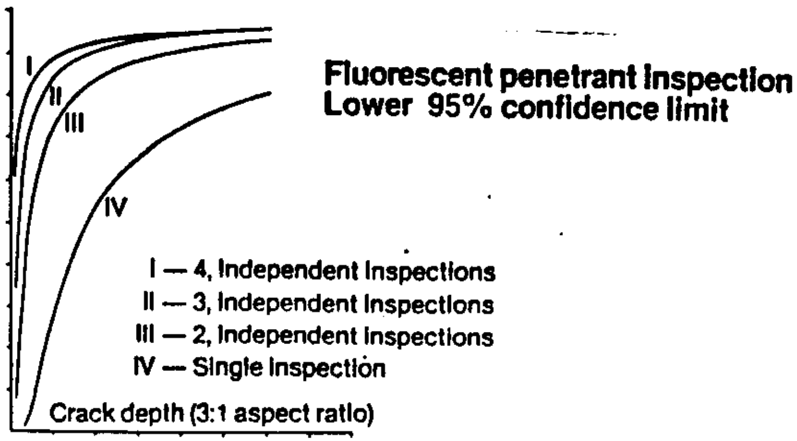


Figure 31 - Probability of Detection - Fluorescent Penetrant Inspection (FPI)



Magnetic Particle Inspection. (MPI)

MPI is the prefered method for surface crack detection in ferromagnetic materials. It is a commonly used technology which can be cheap and quite simple to use. It can be used to detect surface breaking and major near-surface defects. It can be performed using either a dry powder of a liquid which holds magnetic particles in suspension.

In addition to the magnetic particles this technique requires the presence of a magnetic field. Where this field leaks out of the material under test due to the presence of a defect the magnetic particles are attracted. On large components a high magnetic field is required and the field needs to be perpendicular to the edge of the discontinuity.

The leakage fields in a broken bar magnet are shown as Fig 33. The magnetic particles collect in the leakage field generated by defects. A major requirement is the application of a magnitisation field. This is shown as Fig 34. The effect of direction (defect orientation) on detectability is shown as Fig 35.

In many cases a powerful electromagnetic yoke is employed to apply the field. Fig 35) For good detection performance the defects need to be perpendicular to the magnetic field lines. From data given in Table 5 MPI in the laboratory is capable of detection 0.75 mm surface cracks. In production this limit goes to 2.5 mm and inservice inspections have a limit of 6.0 mm. Little data is currently available in the public domain to give give POD data. Work is in progress to seek to make this technology more effective and to quantify its performance. Given a good field geometry and well orientated defects it can be quite an effect technology.

There are major potential problems with the need to need to demagnatise a sample and ensure the removal of the magnetic material which has been applied.

Various groups have been engaged in magnetic field calculation to seek to understand MPI better. Also various forms of detectors, such as the hall probe, have been scanned across defects to get a quantitative measure of field strength.

References.

Quality technology and Metals Handbooks (See introduction).

More detailed treatment is given in;

Magnetic Particle Testing, (1975) NDT Monograph M1, 43 pp British Institute of NDT, Northampton UK.

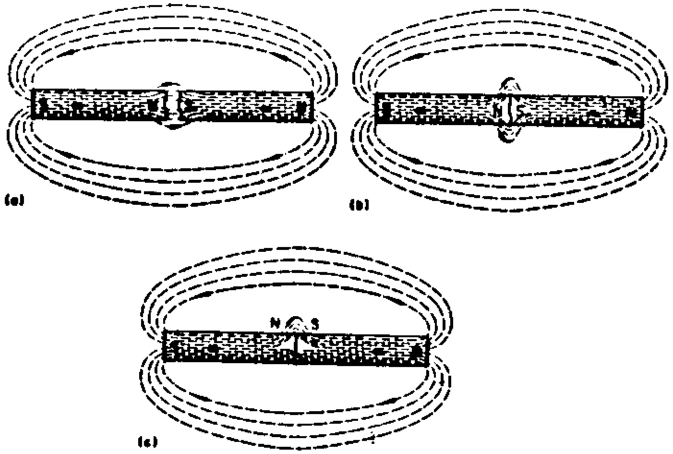


Fig 33.

. Leakage fields between two pieces of a broken bar magnet: (a) with magnet pieces apart, and (b) with magnet pieces together (which would simulate a flaw). (c) Leakage field at a crack in a bar magnet.

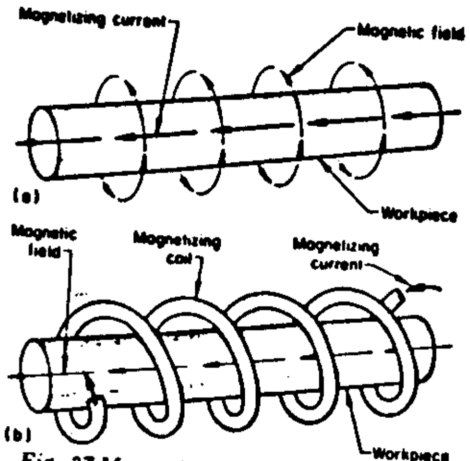


Fig. 32 Magnetized bars showing directions of magnetic field: (a) circular and (b) longitudinal

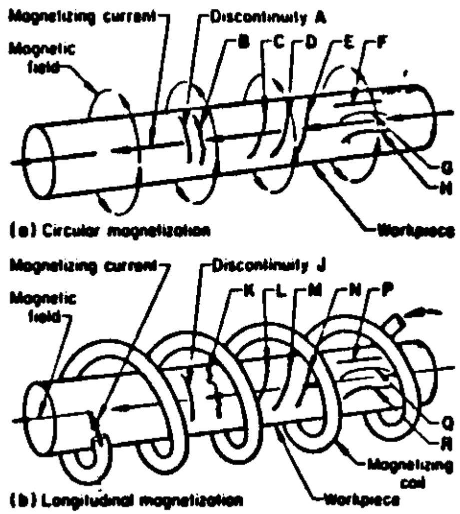


Fig. 35 Effect of direction of magnetic field or flux flow on detectability of discontinuities with various orientations.

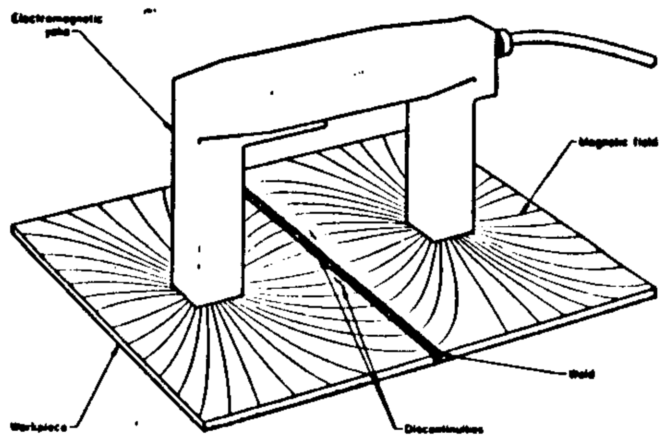


Fig 34 *Electromagnetic yoke, showing position and magnetic field for detection of discontinuities parallel to a weld bead. Discontinuities across a weld bead may be detected by placing the contact surfaces of the yoke next to and on either side of the bead (rotating yoke about 90° from position shown here).*