The McGraw-Hill Companies

Non-Destructive Test *and* Evaluation of Materials

Second Edition

The McGraw-Hill Companies

Non-Destructive Test *and* Evaluation of Materials

Second Edition

J Prasad
C G Krishnadas Nair

Tata McGraw-Hill Publishing Company Limited
NEW DELHI

McGraw-Hill Offices

New Delhi New York St Louis San Francisco Auckland Bogotá Caracas
Kuala Lumpur Lisbon London Madrid Mexico City Milan Montreal
San Juan Santiago Singapore Sydney Tokyo Toronto

Tata McGraw-Hill

Published by Tata McGraw-Hill Publishing Company Limited,
7 West Patel Nagar, New Delhi 110 008.

ISBN (13): 978-0-07-070703-0
ISBN (10): 0-07-070703-0

Vice President and Managing Director—Asia Pacific Region: *Ajay Shukla*
Executive Publisher—Professional: *R Chandra Sekhar*
Asst. Sponsoring Editor—Science, Technology and Computing: *Simanta Borah*
Production Executive: *Rita Sarkar*
Manager—Sales and Marketing: *S Girish*
Deputy Marketing Manager—Science, Technology and Computing: *Rekha Dhyani*
General Manager—Production: *Rajender P Ghansela*
Asst. General Manager—Production: *B L Dogra*

Typeset at Text-o-Graphics, B1/56 Arawali Apartment, Sector 34, Noida 201 301 and printed at
Gopsons Papers Ltd., A-2 and 3, Sector 64, NOIDA-201 301

Cover Design: Kapil Gupta, Delhi

RXCYCRLCDDCXZ

To

The galaxy of past and present contributors to the field of NDE, in all humility

Foreword

Non-Destructive Test and Evaluation (NDE) is a critical component of engineering activities like design, manufacture, certification, inspection, life cycle management and repair. However, educational institutions do not provide a systematic education, training and exposure to practical dimensions of NDE problems as experienced by hi-tech as well as general engineering industries. This aspect needs serious attention.

Further, galloping pace of development of materials and fabrication technologies, coupled with increasing demand from design and maintenance agencies requires that NDE technology keeps pace with these developments.

Non-Destructive Test and Evaluation of Materials is a sincere attempt by authors towards fulfilling this objective. I am sure this effort will go a long way to meet NDE education and training needs of new entrants and professionals to the field.

Baldev Raj
FTWAS, FNAE, FNA, FASc, FNASc
Scientist & Director
Indira Gandhi Centre for Atomic Research
Kalpakkam

Preface to the Second Edition

Non-Destructive Test and Evaluation (NDE) has influenced human civilization from time immemorial. It has been instrumental in improving quality of human life through NDE tools of 'sight and sound', which have significantly helped shape and improve our perception of the physical world around us. However, NDE technology, as we perceive it today came to focus during World Wars I and II.

In the second edition of the book the contents have been reviewed and rearranged to include additional topics of interest. Also some errors that existed in the first edition have been corrected.

Human greed and desire of exploitation by a few has led to enormous distress and suffering to mankind. A tragedy like Bhopal in India, where thousands were killed, and even after quarter of a century, thousands are still suffering from somatic and genetic disorders, could have been averted if adequate NDE warning systems for detecting leak of toxic gases had been provided. Another area of great concern is the lack of integrity on the part of a few NDE professionals under the influence of unethical managements. Awareness, education and training in this area will go a long way in assuring personal integrity and commitment to social responsibility. Keeping this in mind a topic on Ethics and Morality has been introduced in the first chapter.

NDE methods are widely used in Mining Industry. This topic has been included as continuation of *Industrial Application of NDE.*

Fibre reinforced composite materials are finding ever increasing application in aerospace, aeronautics, automobile, electronics and many other industries. NDE has become an essential tool for test, evaluation and certification of fabrication processes. Components and assemblies are subjected to test, evaluation and certification during assembly and service as a mandatory requirement. Repair of composites is an essential requirement in the production and maintenance of composite structures. Keeping these in view, a separate chapter on *NDE of Fiber-re-inforced Composites* has been added, which provides specific test methods and brings out a range of defects encountered during fabrication, service and repair. Effect of various defects on mechanical properties has been discussed and effectiveness of test methods has also been highlighted.

Use of NDE in industries is increasing at a frenetic pace. An attempt has been made to include a collage of pictures giving a bird's eye view of the wide range of NDE applications.

It is hoped that these additions will enhance utility of the book for professionals as well as for new entrants to the field of NDE.

Suggestions from professionals and trainees to improve the book are most welcome.

J Prasad

C G Krishnadas Nair

Preface to the First Edition

Non-destructive Test and Evaluation (NDE) has influenced human civilization from time immemorial. It has been instrumental in improving quality of human life through NDE tools of 'sight and sound', which have significantly helped shape and improve our perception of the physical world around us. However, NDE technology, as we perceive it today came to focus during World Wars I and II.

Different factors like the efforts of defence establishments, accident of 'Aloha Airlines', discovery of intergranular stress corrosion cracks in nuclear BWRs, fatigue cracks in structural components subjected to cyclic load, growth and propagation of defects in engineering components during service, etc. have brought to sharp focus, the demand for consistency of production quality, as well as need of an efficient and cost-effective life cycle management of structural components. This has led to a paradigm shift in design philosophy from 'fail safe' concept to 'damage tolerant concept', necessitating non-destructive monitoring of components during fabrication and service.

Today, the strategic sectors of defence, space, aeronautics, electronic information technology, atomic energy, power sector, railways and roads, consumer industries, material processing, protection and restoration and authentication of cultural heritage use NDE as a mandatory requirement. It is an indispensable part of modern technology and has emerged as a critical component of engineering environment. It is vital in analysis of systems for safety, reliability and mission assurance.

The period after World Wars witnessed development of instruments that could bring out hidden defects in materials/components. Developments in the field of electronics during 1950s provided significant support that led to improvement in sensitivity and portability of instruments.

During 1960s and 1970s with the introduction of acoustic emission, interferrometric and infrared methods there was a wide expansion in the scope of NDE application. 1980s and later witnessed a galloping trend in the development of sophisticated materials, fabrication technologies, coupled with innovative design methodologies, cost effective approach to life cycle management and thereby added emphasis on material characterization in addition to probability of defect detection (POD). With such a demand on NDE technology, it is unfortunate that academic institutions have hardly taken any step to provide a systematic education and training programme to new entrants to the field of NDE.

NDE is a multi-disciplined technology and entrants to this field come from a wide range of educational and technical backgrounds. This book is an attempt to serve the needs of professionals, students and trainees, associated with various disciplines of NDE technology, alike.

J Prasad
C G Krishnadas Nair

Acknowledgements

During planning, designing and scripting of this book we received support and encouragement from various quarters. We are particularly thankful to Dr Gemson, the principal of MVJ Engineering College and Mr Annu Lakshman for providing typing facilities and other related office assistance. Ms Mallika Prasad has been of great help in preparing illustrations and in proof-reading the manuscript. Her support is thankfully acknowledged. We are also thankful to Dr Baldev Raj and his team for carefully going through the manuscript and making meaningful suggestions.

We have referred to ASTM E155, reference Radiograph, for guidelines on acceptance limits of various defects, and to Recommendations of International Commission on Radiological Protection for indicating protective barriers for X-ray and Gamma ray shielding. Their contribution is deeply appreciated.

Last but not least, authors are indebted to various scientists, technologists and engineers who have contributed directly or indirectly in bringing the technology of NDE to its present stage.

J Prasad
C G Krishnadas Nair

Contents

1 Introduction

1.1 Non-destructive Test and Evaluation Technology: An Overview

Non-destructive Test and Evaluation (NDE) is aimed at extracting information on the physical, chemical, mechanical or metallurgical state of materials or structures. This information is obtained through a process of interaction between the information-generating device and the object under test. The information can be generated using X-rays, gamma rays, neutrons, ultrasonic methods, magnetic and electromagnetic methods, or any other established physical phenomenon.

The process of interaction does not damage the test object or impair its intended utility value. The process is influenced by the physical, chemical and mechanical properties as well as by the fabrication procedure of the test object.

Thus, the entire range of methods used to determine the soundness of materials and structures, without impairing their serviceability, is termed Non-destructive Testing (NDT). Its main feature is that unlike other test systems, it does not destroy or damage the test object beyond designed usage. NDT methods, independently or in combination, generate information in a "cradle to grave" life cycle—from product design, development, manufacture and usage to rejection and replacement.

1. Design related information	Strength, stiffness, dimensions, and characterization of micro and macro features of materials, isotropy and residual stresses.
2. Material and process related information	Material homogeneity, presence of defects, location, size and volume dispersion of defects. Health of manufacturing process, its repeatability and confidence level.
3. Service and maintenance related information	Extent of deterioration due to environmental effects, for example changes in material homogeneity and dimension, corrosion, erosion, damage due to fatigue, creep and impact damage due to lightning. Adequacy of repair and replacement of materials and structures.

While evaluating the information generated at various stages, one should keep in mind that NDT methods produce indications on the integrity of materials and structures by indirect means. These indications need to be interpreted properly to determine the conditions that caused them and whether the indications make a specific object suitable for its purpose.

Experience shows that in any engineering environment, the objective of any NDE is as follows:

1. Design stipulated standards (e.g. dimension, strength and stiffness) do not deviate beyond permissible limits and immediate action is initiated in case of such deviations.
2. To establish reproducibility of the fabrication process for successive batches of production with minimum rejection or repair.
3. To establish reliability of NDT methods so that potentially harmful defects, damages, material inhomogeneities or dimensions are noticed while minor defects or deviations do not lead to unnecessary rejection or repair.

The science and technology of NDE involves the following:

- A device that interacts with the test object and generates information
- Knowledge of material and fabrication process
- Understanding the mechanism of interaction between the information-generating device and the test object
- Adequate tools (hardware and software) to capture and record the results of the interactions
- Analysis of generated information and its correlation with test object conditions that caused them
- Presentation of results
- Evaluation of the test object based on results of interaction with the information generating source
- Decision on accept/repair/reject, keeping in view the design stipulation and usage environment
- Communication, documentation and archiving for future retrieval of usable information

Figure 1.1 shows these steps.

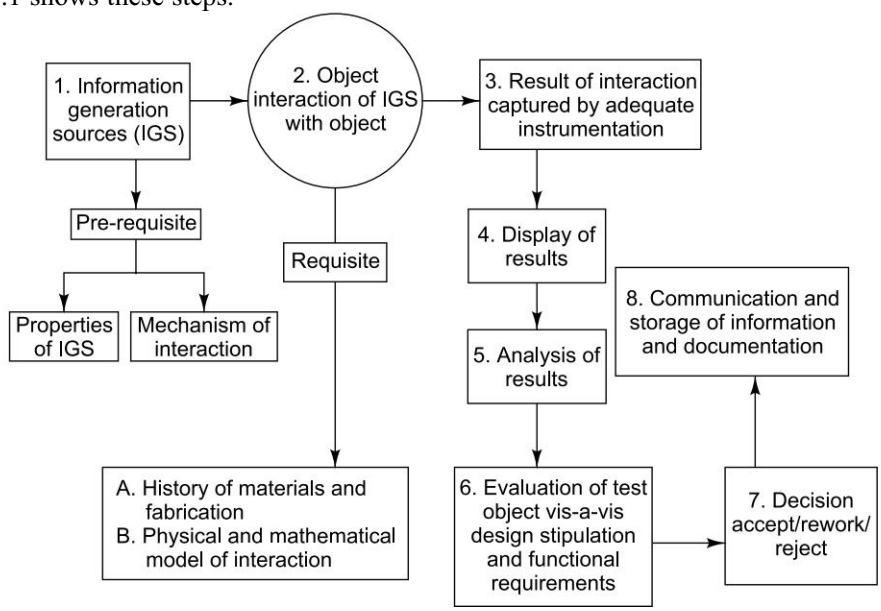


Fig. 1.1 *Steps in Non-destructive Test and Evaluation of Objects/Systems*

1.1.1 Factors Influencing the Reliability of NDE

Each NDT method charts a particular domain of testing. This means that each method is most effective only in a particular area of testing. Two or more methods of testing may complement each other but are not used for cross-checking the effectiveness or efficiency of each other. The success of any NDT method depends on its adequacy and reliability for a particular test situation. This will be clear as we discuss specific methods of NDT in later sections. The major factors that influence the reliability of NDT methods are:

1. Human factors	Education, training, experience of NDT personnel and working environment
2. Testing method	Adequacy of NDT method, specific technique of testing, standardization, standards and database related to testing
3. Test object	Complexity of shape, accessibility in case of assemblies, material characteristics, surface condition
4. Nature of defect or discontinuity	Location, nature, size, shape, volume dispersions
5. Knowledge base and facilities	Understanding of the mechanism of interaction between the test object and the information-generating tool, adequacy of hardware and software skills of data presentation
6. Risk factors vis-à-vis functional requirements	Probability of defect detection, structural significance of single or dispersed defects or the probability of failure. Statistical data for reliable decision-making

Each of these factors need to be studied in depth for effective utilization of the product during its designed life as well as for a realistic extension of its designed life. Laxity could result in cost escalation, time over-run and loss of goodwill in a competitive market.

1.2 Materials, Manufacturing Processes and Non-destructive Testing Materials

The major materials used for engineering activities are grouped into four classes, namely, metals and alloys, ceramics, polymers and composites. Each of these materials has a distinct property profile. A brief description of their properties and applications follows.

Pure metals find limited application, while metals and alloys (ferrous and non-ferrous) are the most widely used engineering materials. Table 1.1 gives the properties and engineering application of various materials.

1.2.1 Manufacturing Processes and Defects in Materials

Materials are subjected to many manufacturing processes to produce not only the desired shape but also to ensure the design-stipulated physical and mechanical properties and dimensional tolerances. Further, components are provided with necessary surface protection from corrosion and erosion. However, all manufacturing operations and service environments induce various types of defects in engineering components, which need to be detected and evaluated through non-destructive methods. Table 1.2 gives major manufacturing processes and defects encountered during manufacturing and service.

TABLE 1.1 *Property and application of materials*

Materials	*Properties*	*Application*
Metals and alloys (ferrous and non-ferrous)	Good thermal and electrical conductivity, high strength and stiffness, ductility, malleability, hot and cold workability, weldability	Fabrication of structural components and assemblies for general engineering as well as high-tech application in such areas as aerospace, aircrafts, automobiles, railways, atomic reactor vessels, electrical and thermal conductors, offshore and deep sea exploration
Polymers (includes a variety of materials like rubber, plastics and adhesives)	Light weight, corrosion resistance, low strength and stiffness, electrical insulation, low coefficient of friction, poor resistance to high temperature	Structural and decorative items, paints, adhesives, car tyres and doors, home appliances, trash bags, potholders, wire insulation, computer chips, packing materials
Ceramics (inorganic non-metallic materials, constituents of which are bonded together by covalent or ionic bonds)	Low density, good temperature and corrosion resistance, high melting temperature, brittleness, abrasive, piezo-electric properties, good optical properties	High temperature applications, fabrication of transparent windows, pottery making, abrasives

1.2.2 Composites

Composite materials may be defined as—materials made of two or more dissimilar materials, brought into adhesive combination by application of heat and pressure over a period of time.

The property of composite materials is different from and superior to any of its constituents and constituents do not react chemically. One of the constituents of the composite material is called the Matrix. It acts as a binder. Its function is to retain the shape of the structure, protect and stabilize reinforcement and to transfer load to and between reinforcement materials. The other component is called Reinforcement. The reinforcing material provides strength, stiffness and low thermal expansion.

The following materials are used as a matrix: polymers, glass, carbon and metals. Reinforcing materials are: alumina (Al_2O_3), aluminum (Al), boron nitride (BN), beryllium (Be), glass graphite, Aramid (Kevlar), silicon carbide (Sic), silicon nitride (Si_3N_4), titanium (Ti) and tungsten (W).

Reinforcing materials are used as particles, whisker, wire or fiber (continuous, discontinuous, woven or foils).

Thus, we have:

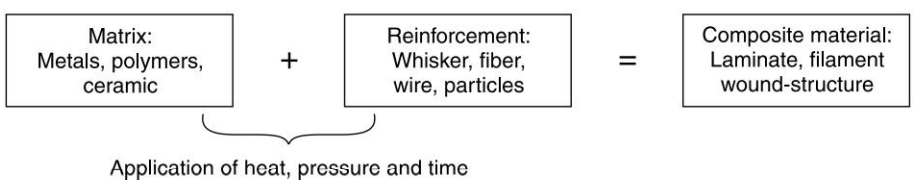


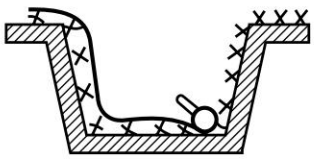
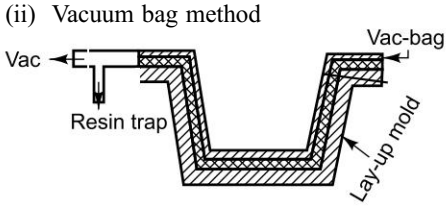
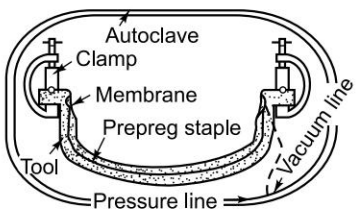
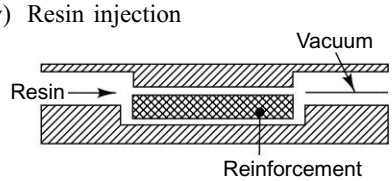
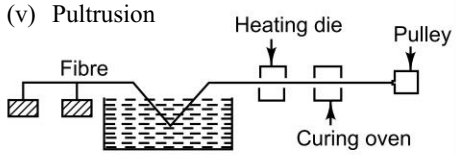
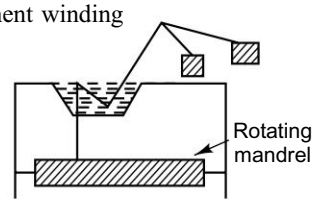
TABLE 1.2 *Major manufacturing processes*

Manufacturing Processes/Service Environment	*Defects Encountered during Manufacturing and Service*
Casting: Sand, die cast, permanent mold, investment and continuous casting	Inclusions, segregations, gas pockets, internal shrinkage, surface crack, pipes, gas porosity, hot tears, cold shuts, cavities
Welding: Gas welding, resistance welding, arc welding, friction welding, brazing, soldering and diffusion bonding	Lack of fusion, incomplete penetration, cracks, slag inclusion, gas porosity, crack in parent metal, root undercutting
Forming: Forging, rolling, wire drawing, deep drawing and bending, extrusion	Inclusion, segregation, pipes, seams, laps, bursts, cracks, tears, lamination, flakes, rolled-in scale, roll mark, die-mark, thermal crack
Machining: Cutting, drilling, turning and milling	Cracks, nicks, scratches and ridges, tears and laps, hardness alteration, residual stress distribution, deformed debris, grain size change, inter-granular corrosion, embrittlement cracks
Powder metallurgy: Compressing of metal powder into solid mass by application of pressure and heat	Porosity, cracks, inclusion, variation in density distribution
Heat treatment: Specific to alloys to impart desired microstructure, hardness, strength and stiffness	Cracks, segregation, grain size changes
Surface protection: Surface protection of components is provided by organic, inorganic and metallic coating: (i) Organic coating: Paints and lubricants (ii) Inorganic coating: Phosphating and chromating (iii) Metallic coating: Electroplating, coating by diffusion e.g. galvanizing, aluminizing, metallizing by a spray of partially melted material	Dents, scratches, change in thickness of coating, insufficient protection of surface, erosion of protective coating

1.2.3 Fabrication of Composites

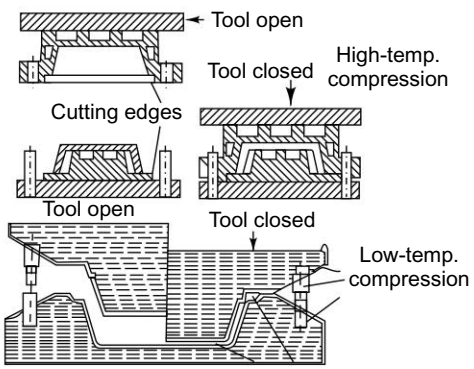
Fiber-reinforced polymer components are thermoset or thermoplastic. Thermoset composite parts are fabricated by lay-up of unidirectional tape on a mold of desired shape and configuration. The laid-up tape is compacted and subjected to a cure operation. This operation turns the resin and fiber combination into a stiff structural component. The major fabrication methods and salient features for thermoset components are presented in Table 1.3.

TABLE 1.3 *Fabrication methods and salient features for thermoset components*

Methods	*Salient Features*
(i) Hand lay-up 	The method is simple and suitable for simple components. A coat of resin is applied on a tool surface and a layer of mat or fabric reinforcement is placed on the tool surface. The process is repeated till the required thickness of the laminate is reached. This is cured at 25–40°C. No pressure is required.
(ii) Vacuum bag method 	Lay-up of laminates is covered by an airtight rubber membrane and the air under membrane is evacuated, which helps compaction and removal of air bubbles. This is cured at 25–40°C at a pressure of 1 bar.
(iii) Autoclave method 	This method is similar to the vacuum bag method. The laid-up assembly is covered with an airtight assembly and sealed against the tool. The assembly is then placed in an autoclave where vacuum, pressure and the cure process is tightly controlled.
(iv) Resin injection 	This method requires top and bottom halves of tools whose shape corresponds to the desired thickness and configuration of the part. The re-enforcing materials, in the form of fabrics or mats, are placed between the tool halves in dry plate. The resin is injected by means of vacuum. The system is cured at 25–40°C at a pressure of 1 bar.
(v) Pultrusion 	This is the reverse of extrusion. Material is pulled through a die. This method is used for producing straight lengths of solid or hollow cross-section.
(vi) Filament winding 	Resin-covered continuous rovings, bands or mats are placed on a rotating mandrel and cured. This method is used to produce parts with circular, elliptical or oval cross-sections.

(*Contd*)

(*Table 1.3 Contd*)

Methods	*Salient Features*
(vii) High and low temperature compression molding 	As in the case of resin injection, the top and bottom tool halves are required. Resin is poured into the lower tool half, followed by placement of a prepared staple of weaves or mats. Closure of the tool under pressure causes the resin to penetrate the reinforcing material.

Thermoplastic resins are polymerized before the fiber-reinforcements are added. These are capable of being softened by increasing temperature and hardened by a decrease of temperature. These materials are commercially available as pre-pregs, tapes and sheets.

The following methods are used for producing components:

1. Hot stamping: to produce plane or simple curved parts
2. Super plastic forming: to produce parts with medium geometric complexity
3. Autoclave technique: to produce flat laminates
4. Filament winding: to produce components with regular geometric cross-section
5. Melt impregnation technique: to produce laminates for sandwich type assembly

1.3 Designs and Non-destructive Testing

The objective of a design engineer is as follows:

(i) To conceive and design the shape and configuration of a component or assembly of engineering systems.

(ii) To visualize the functional environment of the structural component and estimate the required physical and mechanical properties for it to sustain service and environmental constraints.

(iii) To select suitable material and a commensurate manufacturing process to realize the designed shape and required physical and mechanical properties in a cost effective manner.

(iv) To appreciate the variability of manufacturing processes that lead to statistical variation in physical and mechanical properties, which necessitates the stipulation of tolerance margins with respect to mechanical properties and dimension. Further, it is important to appreciate that too close a tolerance margin leads to rejection and increases the cost of production, while a liberal margin increases the risk of failure.

(v) To realize the fact that structural components undergo degradation or damage during service.

Keeping these factors in view and the reliability requirements of high duty components, the designer's approach to design is based on a 'fail-safe' concept or 'damage tolerant' concept. The 'fail-safe' concept means that the component would be replaced after its designed life is reached. The reliability of such a component is based on 'not permitting' any defect during the manufacturing stage or assuming that any defect present during manufacturing does not affect its service life due to applied safety factors.

However, it is practically impossible to accept this approach in any real life situation. Many catastrophic failures in engineering systems have pointed to serious limitations of this approach to design.

The current approach to design of structural components is based on the 'damage tolerance' concept. The concept accepts the reality of the presence of defects from the beginning, which may grow during service. It is stipulated that in the presence of defects up to a certain limit, failure of the structural component has a very low probability (~ 10^{-4} to 10^{-6} probability of failure) within a defined time interval of service. After this time interval, the possibility of continued usage, repair or rejection of the structure is decided by periodic inspection.

Now, let us examine how NDE fits into the wide spectrum of design, manufacture and life cycle management activities of engineering systems. NDE plays a significant role at various stages of design, manufacture and life cycle management of engineering structures. Table 1.4 shows NDT support to various activities from the design state to maintenance and extension of operational life.

TABLE 1.4 *NDT support at stages of design, manufacture and life cycle management*

Activity	*NDT Support*
Design and product development	1. Statistical evaluation of strength, stiffness and dimensional features 2. Detection, location, sizing and volume dispersion of defects 3. Assessment of variation in material homogeneity, isotropy, residual stresses
Manufacturing stage	1. Assessment of repeatability of manufacturing processes for different batches of production 2. Detection, location, sizing and volume distribution of defects and material in-homogeneity 3. Providing acceptance criteria for defects and material in-homogeneity
Life cycle management	1. Estimation of variation in material homogeneity, dimensions due to corrosion, erosion, irradiation, damage due to fatigue, creep, impact and lightning strike 2. Generating defect-property correlation data and specific information related to life extension of components. Determination of adequacy of repair or replacement of materials and structures 3. Preparation of specifications/documents/test techniques for periodic NDT inspection for health monitoring and to determine the stage of damage in a structure till it reaches the critical stage of rejection and replacement

Broadly speaking, the growing industrial scenario demands a close interaction between design engineers and NDT engineers to cover:

- Structure/assembly inspectability using NDT methodology
- Ensuring the damage tolerance concept of design by integrating NDT into design and manufacturing processes and risk assessment activities
- Incorporating the statistical approach in developing acceptance criteria for design stipulated properties. Statistical study of all critical parts focusing on failure susceptible zones under services and environment loads, and development of NDT techniques considering accessibility, limitations owing to shape and/or assembly features and preparing a database

While applying NDE techniques, it is important to keep the following in mind:

- A discontinuity or material in-homogeneity is not a defect unless it reduces design stipulated properties and dimensions. Further, the significance of a defect or material in-homogeneity varies according to its location in a given structure or assembly and the nature of stress around it. This factor assumes importance while accepting, rejecting or repairing a structure and during failure risk assessment to extend operational life of structural components in a given load environment.
- NDT engineers, while developing a technique for test and evaluation of a structure, must consider such factors as adequacy of NDT equipment, complexity of structure, nature of defects, available expertise for interpreting an NDT indication and the probabilistic nature of defect detection. Also, it needs to be appreciated that the probability of defect detection (POD) depends on the material of the structure under examination, component configuration, location, nature and distribution of defects and the NDE technique selected. Any method developed must demonstrate 90% of the POD for the smallest acceptable defect. Hence, the NDT engineer and structure design must realistically fix a minimum size of acceptable defect, considering equipment, skill of personnel and testing environment. The capability of each of the NDT methods to detect the minimum size of defects is discussed under specific NDT methods. POD is also connected to the probability of failure (POF) of the structure and depends on materials, distribution and nature of flaw (propagative or non-propagative) and load history.

1.4 Ethics, Morality and Technology of NDE

Evoluation of societies has been influenced by ecological environment as well as by ethics and morality. The concepts and perceptions of ethics and morality essentially implies:- 'What is right and good as against what is wrong and evil' in conduct of activities of individuals and societies'. Individuals and societies evolve over a period and stipulate standards for guidance in conduct of their activities based on religion, customs and experience. These standards form the basis for moral and ethical concepts and provide guidance in conduct of activities of individuals, societies and families.

It is interesting to examine general codes of ethical and moral codes or statement of values and beliefs considered acceptable globally:

1. Individual or collective activities must ensure integrity that invites trust of community.
2. Individual or collective action must enhance reputation of societies, industries and the country.
3. Individual or collective service must be rendered unselfishly.
4. To display fairness and honesty in expressing opinion, making statements or in giving evidence based on personal knowledge and competence.

5. In Industries, personnel at all levels must realise that individual greed, poor management, poor workmanship can adversely affect work environment, safety and moral of workers.

In practical life, implementation of codes presents difficulties because of different perceptions, value systems in different societies and lack of legal sanctions and enforcement mechanisms. Factors like greed, desire to exploit; aggravates the situation further. This concern has led to a global movement to adopt ethical codes of conduct and reinforce them through education and training programmes.

In so far as the technology of NDE is concerned, it is interesting to note that NDE has great money spinning potential and it occupies a critical position in any engineering environment. A technology with a wide range of application and capability to provide effective support to design, manufacture, life-cycle management and risk assessment activities, is bound to impinge on decision making process, maintenance of moral, resource conservation and efficiency of management. This is possible only if norms of moral and ethical standards are maintained. Non adherence to these standards could lead to disastrous results. A few observations, based on real incidents, given below bring out a host of problems arising out of unethical conduct: -

1. A large company, engaged in welding of pipes and plates outsourced the work to another company stipulating acceptance norms. One of the conditions was that a representative sample of the weld for each batch was to be radiographed and submitted along with radiographic report of welded items. Over a period, it was accidentally found, by a senior reviewer that sample radiographs for different batches of welding were same, only the identification numbers were changed.

   In addition, other unacceptable defects were also observed. Further investigation showed that the welder and supervisor were aware of what was going on but none had the courage to bring out the truth for fear of loosing the job.

   This is obviously a case of greed and dishonest business practice, where all norms of ethics and morality were utterly ignored. This was also an instance of workers being pressurized and demoralized. Another issue that crops up from this case is the possibility to provide protection and immunity to workers from pressure of management.
2. A company "X" placed an order on another company "Y" to supply some critical Magnesium alloy castings. The suppliers were well known for their capacity and capability. However, it was observed that the supplied castings were getting rejected during machining. An in depth investigation (Radiographic, Metallurgical and Chemical) showed that the castings contained a significant number of hard particles (Nitrides). Usually, during pouring of melt in the casting mould, the last remains of the melt in the crucible is discarded as it contains unacceptable elements. Obviously, normal foundry practice was not followed, leading to loss of time, money and non-meeting of schedule by the company. The question that crops up is; why a renowned company did not follow normal quality control procedures before supply of castings? Was this unethical act a result of greed, to take advantage of non availability of facilities at customer's end?
3. A head of a forging company got some forgings made out of a wrought stock which was initially rejected by a metallurgical laboratory. One of the components showed a forging lap in the liquid penetrant test. It was decided by the head of quality control to scrape the material till the lap was removed, conduct another liquid penetrant test and accept the component if no defect indication was observed. Accordingly, after removal of material and retest the component was accepted. It so happened, that the same component failed in service. At the junction of failure remains of the penetrant liquid was noticed.

The inspector who accepted the component was held responsible for the failure and was punished. It was noticed in due course that there was no document on procedure for salvaging defective components. It is a known fact that in soft materials like aluminum alloys, scraping in a direction transverse to the defect leads to smearing of the material. In the process, the defect is covered and fails to show in penetrant test. This case brings out the following points:

(a) Was it right for the head of the organization to order use of a wrought material which was initially rejected?

(b) Why head of quality control department did not issue specific document for salvaging such components?

(c) In view of the above case, was it ethical and moral to punish an inspector at lower level?

This kind of situation is often observed in manufacturing organisations.

These instances are just tips of iceburg. Human greed and desire of exploitation by a few has led to far bigger disasters and suffering to mankind. Disasters like accident at Bhopal in India where thousands were killed and even after quarter of a century thousands are suffering from somatic and genetic effects might have been saved if adequate NDE warning system for detecting leak of hazardous chemicals had been provided. In fact, installation of such devices alert, workers to escape in time and accident is prevented. Installation of NDE warning system to detect toxic and dangerous gases can save many lives in mining Industry where criminal neglect of managements leads to many avoidable deaths and sufferings.

In today's global environment where criminals, terrorists, drug-mafia and unethical action of corrupt politicians is inflicting untold miseries on humanity, the technology of NDE can play a significant role to improve the situation.

Non-destructive tests detect weapons, explosives, drugs, chemicals, bombs, hijacker implements by application of radiographic and electromagnetic tests. Drug traffic and movements could be controlled by using sensitive NDE methods. Further it is necessary to integrate advances made in other branches of science and technology in to the fold of NDE to make it more effective in control and monitoring of unethical human activities. In this regard, specific mention may be made of: integration of digital and video data testing system with vast developing communication methodology in to the technology of NDE, application of remote sensing devices for monitoring and control of human and material movement in outer space and under sea and detection of objects buried in the earth. Development of Sensitive NDE test system for detection and warning related to radiation hazards, fire, leak of toxic gases/elements.

Another area of concern is lack of personal integrity which results in tampering of test results under the influence of unethical managements. The education and training of NDE professionals must ensure absolute personal integrity of professionals and commitment to social responsibilities.

2

RADIOGRAPHY

2.1 SOURCES OF X AND GAMMA RAYS AND THEIR INTERACTION WITH MATTER

X-rays and Gamma rays are the most commonly used penetrating radiations for industrials radiography.

2.1.1 X-rays

X-rays are produced when high-speed electrons strike a metal target in a highly evacuated glass enclosure (vacuum $\simeq 10^{-9 \text{ to } -13}$ mm/Hg). A metal filament is sealed inside the enclosure, which is heated by a current of a few amperes to produce electrons at its surface. At the other end of the glass enclosure, a high atomic number metal target is sealed, on which the fast moving electrons strike. To accelerate the electrons, high voltage of a few thousand volts is applied between the filament (cathode) and the metal target (anode). This arrangement is shown in Fig. 2.1.

If the applied voltage is 'V' and charge of the electron is 'e', the kinetic energy imparted to the electron is 'Ve'.

If the mass of the electrons is 'm' and acquired velocity is v, then the kinetic energy of the electron is equal to $\frac{1}{2}\, mv^2 = Ve$.

Electrons approaching the target lose their energy in one or more of the following ways:

Cathode electrons interact with free electrons of the target atom and, in the process, lose part of their energy, which is converted into heat and X-rays of low frequency.

The corresponding wavelength of the emitted X-rays is given by

$$\lambda = \frac{hc}{e(V - V')} \tag{1}$$

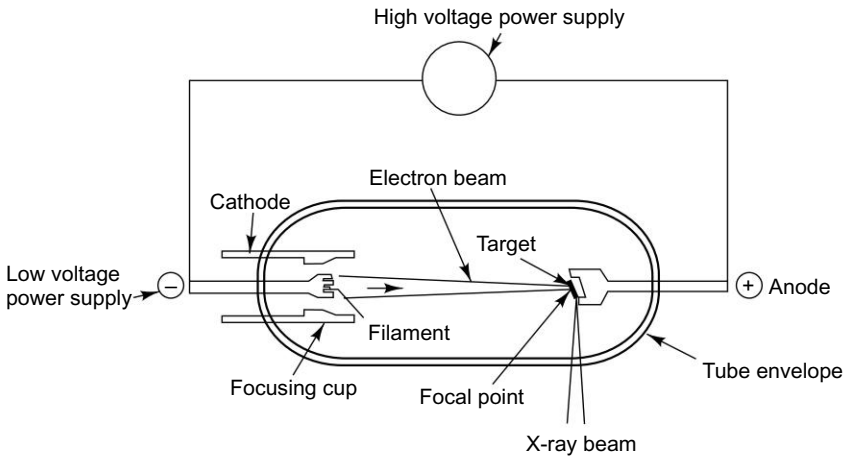


Fig. 2.1 *Arrangement for Producing X-rays*

where

h = Planck's constant

c = Velocity of light

$(V–V^1)\ e$ = Part of the electron's energy converted into heat or X-rays.

(i) Cathode electrons with sufficient energy may reach and be stopped by the heavy nucleus of the target. In the process, the entire energy of the electron is converted into X-rays of wavelength given by:

$$\lambda_{min} = \frac{hc}{Ve} = \frac{12395}{V}\ \text{Å}$$, substituting the value of h, c and e; Å is the Angstrom unit

This wavelength is minimum, corresponding to the maximum energy Ve acquired by the electrons.

(ii) It may also happen that the cathode electron knocks out one of the orbital electrons of the target atom and the atom is subsequently returning to its normal energy state when one of the electrons from an outer orbit falls into the vacancy. In this process, the X-rays of a definite wavelength, characteristic of the target material, are emitted. This is called characteristic radiation.

These processes occur simultaneously and give rise to a spectrum of X-rays as shown in Fig. 2.2.

Effect of Tube Voltage and Current on Intensity of X-rays

The X-ray spectrum is significantly influenced by change in voltage between electrodes of the X-ray tube. Increased voltage leads to increase in generation of shorter wavelength compared to those that were present at low voltage. Also, the intensity of the X-ray beam increases significantly and is given by the relation:

$$I = KV^2$$

where K is a constant.

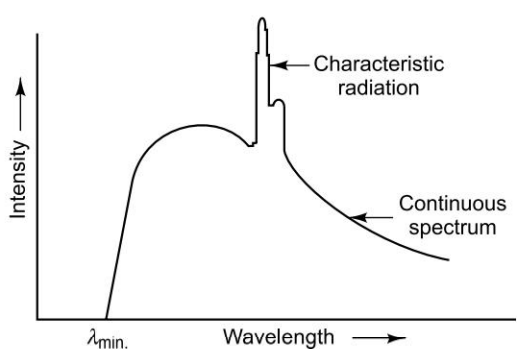
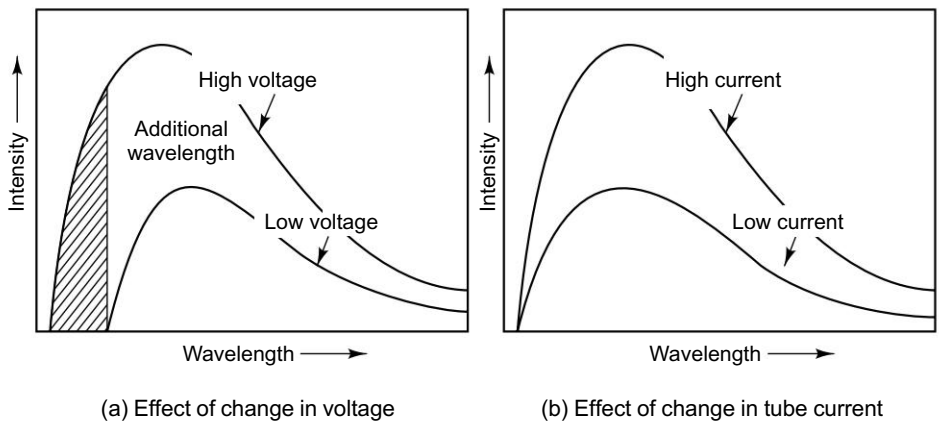


Fig. 2.2 *Spectrums of X-rays*

The intensity also increases as the tube current increases. (Tube current is the current that flows between the cathode and the anode and should not be confused with filament current, which heats the filament to produce electrons at its surface.)

Figure 2.3 shows the effect of increased voltage and tube current on the X-ray spectrum.



(a) Effect of change in voltage (b) Effect of change in tube current

Fig. 2.3 *Effect of Change in Voltage and Tube Current on the X-ray Spectrum*

2.1.2 Gamma Rays

The nucleus of an atom mainly consists of protons and neutrons bound to it. These particles exist in discrete energy levels similar to energy levels of orbital electrons of atoms. The nuclei exist in different energy states. A transition of nuclear energy level from a higher state E_1 to a lower energy level E_2 is possible. In such a transition of nuclear energy, gamma rays may be emitted according to the relation

$E_1 - E_2 = h\nu$, where h is Planck's constant and ν is the frequency of emitted radiation.

Gamma rays are similar to X-rays, except that they are emitted by the nucleus of the atom. Gamma rays consist of discrete wavelengths much shorter than that of X-rays.

2.1.3 Radioactivity

The mass of a nucleus, consisting of z protons and $A–z$ neutrons, is found to be less than the sum of masses of z protons and $A–z$ neutrons. This difference is called *mass defect*. If this mass difference is ΔM, then the energy equivalent of this mass

$E = \Delta Mc^2$ (where c is the velocity of light), is said to be responsible for keeping the constituents of the nucleus bound together.

Coulomb forces between them tend to break the nucleus. However, for the nucleus to be stable, it is essential that the nuclear binding forces overcome this repulsive force. It is found that in elements of atomic numbers higher than 82, repulsive forces are very high and such elements are no longer stable. These elements start disintegrating to form stable elements of lower atomic number.

This disintegration of nuclei of high atomic number, owing to repulsive Coulomb force, is called **radioactivity**. During the process of disintegration, alpha and beta particles and gamma rays are emitted.

Alpha particles (α) are positively-charged particles, with a mass of about four times that of the Hydrogen atom and carrying two units of positive charge. They produce fluorescence, can ionize gases and are easily absorbed by a thin sheet of paper. They are deflected by magnetic fields.

Beta particles (β) are negatively charged particles, identified with electrons. It is believed that they are created during the radioactive decay process. They ionize gases and are deflected by magnetic fields in a direction opposite to the direction of alpha particles. They are easily absorbed by matter.

Gamma rays (γ) are uncharged and not affected by magnetic fields. They are highly penetrating rays, emitted in discrete energy levels.

Radioactive Series

Radioactive elements are divided into (1) naturally occurring radioactive elements and (2) artificially produced radioactive isotopes (elements having the same atomic number but different mass number are called isotopes).

Naturally occurring radioactive elements decay by α and β emission. Radioactive isotopes formed by a sequence of transformations, constitute a radioactive series. A natural radioactive series starts with a long lived element and ends with a stable isotope. There are three such groups.

- Thorium series: Starting with $_{90}Th^{232}$ and ending with $_{82}Pb^{208}$
- Uranium series: Starting with $_{92}U^{238}$ and ending with $_{82}Pb^{206}$
- Actinium series: Starting with $_{92}U^{235}$ and ending with $_{82}Pb^{207}$

Bombarding materials with electrons, protons or neutrons produces artificial radioactive isotopes. Currently, artificial radioactive isotopes are produced by exposing materials contained in aluminum cylinders to a neutron flux in a channel in an atomic reactor core. The nucleus of the substance captures some of the neutrons and is transformed into a radioactive substance. A few examples are:

$$_{11}Na^{23} + {}_0n^1 \longrightarrow {}_{11}Na^{24} + \gamma$$

$$_{27}Co^{59} + {}_0n^1 \longrightarrow {}_{27}Co^{60} + \gamma$$

$$_{77}Ir^{191} + {}_0n^1 \longrightarrow {}_{77}Ir^{192} + \gamma$$

Radioactive Decay

Statistical studies have shown that radioactive disintegration occurring per unit time is proportional to the total number of radioactive atoms present. Mathematically this is represented by

$$-\frac{dN}{dT} = \lambda N \tag{1}$$

where λ = constant of proportionality
N = Number of radioactive atoms present
–ve sign indicates decrease in number with time

If, initially, the number of atoms is N_0 at $t = 0$, then

Expression (1) can be expressed as $N = N_0 e^{-\lambda t}$ (2)

This is the basic law of radioactivity transformation. The constant of proportionality λ is called *radioactive decay constant*. The quantity $\frac{dN}{dT}$, called *activity*, decreases exponentially. It is seen from Equation (2) that the time taken by any radioactive substance to decay completely (i.e. $N \to 0$) is infinite. This information is of no significance. For this reason we consider "Half-life (T)", which is

defined as the time required for half the atoms initially present to undergo transformation. Thus, after half-life we have

$$\frac{N}{2} = Ne^{-\lambda T} \quad \text{or} \quad 2 = e^{\lambda T} \quad \therefore \; T = \frac{0.693}{\lambda}$$

$\frac{1}{\lambda}$ is called the mean life of a radioactive atom.

$\therefore$ **Half-life (T) = 0.693 × mean life**

From the viewpoint of industrial radiography, half-life is a convenient measure of the useful period for which a radioactive isotope can be used economically.

Units of Radiation

The standard unit employed for measuring the strength of a radioactive substance is Curie, which is defined as the quantity of radioactive material giving 3.7×10^{10} disintegration per second. Curie is a large unit; therefore milli-curie and micro-curie are also used as units.

1 Curie = 1,000 milli-curie

1 milli curie = 1000 micro-curie

The SI unit of radioactivity is Becquerel, which is equal to 1 disintegration per second.

1 Becquerel = 1 disintegration/second

1 Curie = 3.7×10^{10} Becquerels

Another unit of radioactivity is Rutherford, which is defined as the amount of radioactive substance giving out 10^6 disintegrations/second.

Specific Activity

Specific activity of a radioactive substance is defined as its activity per unit weight. It is expressed in Curie or milli-curie/gram.

The specific activity of an irradiated substance increases with time of irradiation in the reactor. In practice, specific activity is found to be affected by:

- Impurity of irradiated material
- Variation in neutron flux
- Loss of material due to conversion into radioactive material

Gamma ray sources having high specific activity have small physical dimension and low self-absorption. This aspect is significant from the radiographic viewpoint.

Radioactive Isotopes for Industrial Radiography

Gamma rays emitted by naturally occurring radioactive materials like radium and radon were used for radiography in the early stages. But after 1948, when artificial radioisotopes became available, Gamma radiography has been widely used for industrial radiography. The major artificially produced isotopes suitable for radiography are Cobalt-60, Caesium-134, Caesium-137, Iridium-192, Thulium-170, Sodium-24, Ytterbium-169 and Tantalum-182.

Gamma rays emit discrete wavelengths of radiation, with their own characteristic energy. The energy spectra of some isotopes used for radiography are given in Fig. 2.4.

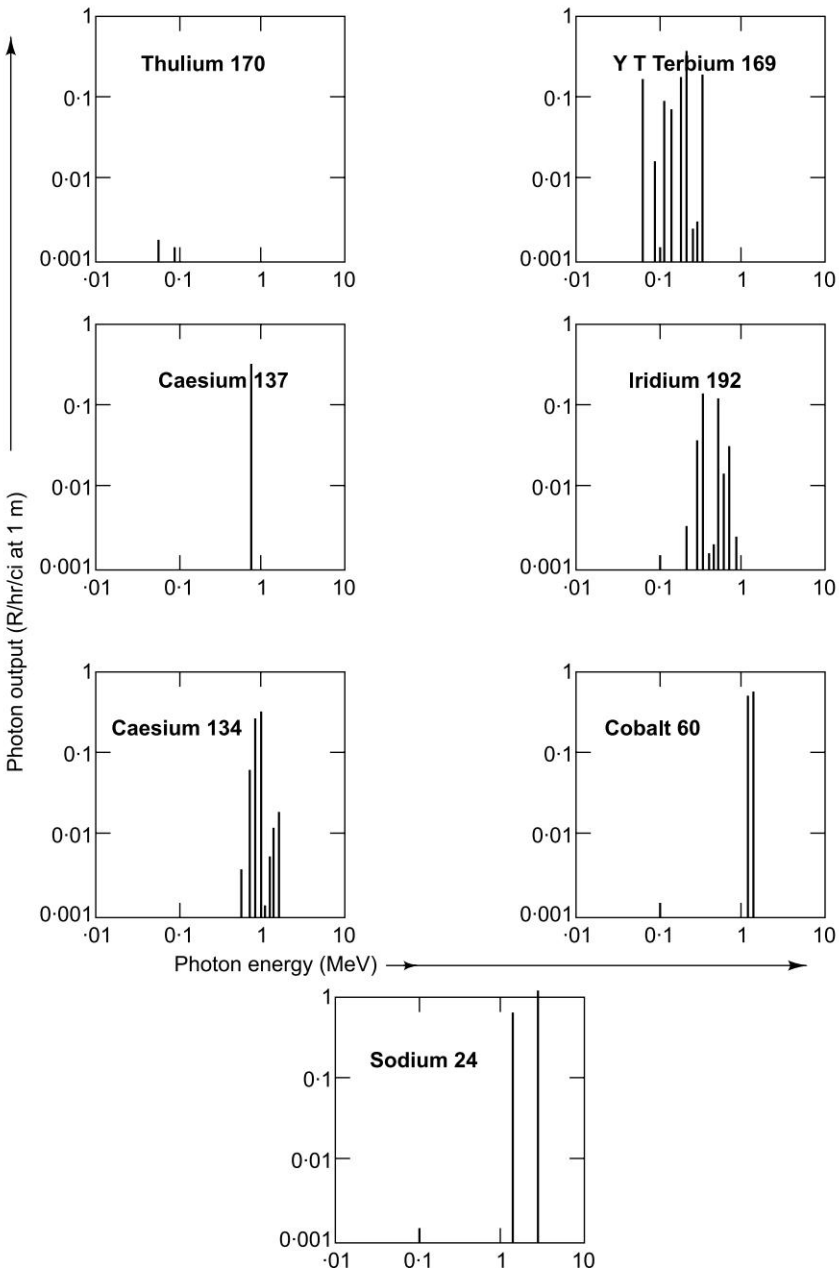


Fig. 2.4 *Gamma Ray Energy Spectra*

Table 2.1 gives the mean energy, half-life and thickness/penetration of isotopes mentioned.

TABLE 2.1 *Half-life, mean energy and penetration in steel*

Isotopes	*Half-life*	*Mean Energy (MeV)*	*Penetration in Steel (mm)*
^{60}Co	5.26 yrs	1.4	230
^{134}Cs	2.10 yrs	0.8	75
^{137}Cs	30 yrs	0.66	75
^{192}Ir	74 days	0.5	75
^{170}Tm	127 days	0.084	12.5
^{182}Ta	120 days	1.2	230
^{24}Na	15 hrs	1.4	–
^{169}Yb	31 days	0.15	25

Units of X-ray and Gamma Ray Measurement

X-ray and gamma ray energy is usually expressed in ergs or electron volts (eV). [1 eV = 1.6×10^{-12} ergs]. From a practical point of view, X-rays or gamma rays energy is evaluated by the effect they produce after undergoing absorption in matter. The physical or biological effects produced by X-ray or Gamma ray absorption is based on the capability of these rays to produce ionization in materials. The unit for their quantitative measurement is based on their absorption and associated ionization in a standard substance. The standard substance selected is 1cc of air at normal temperature and pressure (NTP). Based on this, the unit 'Roentgen' is defined as the quantity of X or gamma radiation that ionizes 1 cc of air at NTP, to produce 1 electrostatic unit of electricity of either sign. Expressed in ergs, this is equivalent to 87.7 ergs.

X and gamma rays are electromagnetic radiations and 'Roentgen' expresses the effect of absorption of these radiations. It is desirable to define units of measurement of all types of radiations that are absorbed by all types of material mediums and not only by air. In view of this, the following units are defined for a wide range of applications:

REP (Roentgen equivalent physical)
RAD (Radiation absorbed dose)
RBE (Relative biological effectiveness)
REM (Roentgen Equivalent man)

REP is defined as that quantity of radiation that produces energy absorption of 94 ergs in soft tissue. Here, soft tissue is used as the absorbing substance instead of 1 cc of air. The average energy for producing ion pair in tissue is 32.5 eV.

RAD is defined as energy absorption of 100 ergs per unit mass of irradiated material at the location of interest. Thus, whenever 'rads' is used as the unit of measurement, the material exposed also must be mentioned.

RBE: A fixed 'rad' dose of different radiations does not produce the same biological effect. Therefore, it is essential to introduce a factor of equivalence. The 'Relative Biological Equivalent' factors are defined as the ratio of the dose required by irradiation with 250 KV X-rays to produce certain biological effects to the dose required to produce the same biological effect. Table 2.2 gives biological effect of ionising radiation and approximate REM value.

TABLE 2.2 *Biological effect of ionizing radiation**

Biological Effect	*Remarks*
1. Whole body irradiation (Blood forming organs)	An exposure of 50–100 REM may lead to fatigue, diarrhea, nausea and death. The effect may develop within hours, days or week, depending on dose of exposure. Longer the dose, sooner a given effect occurs.
2. Cataract formation	The effect of radiation is delayed. It may be induced when dose exceeds approximately 200–300 REM. It may take months or years to appear.
3. Cancer	Studies show that there is potential risk associated with high dose exposure of radiation. Radiation induced cancer may take years to appear.

* Based on the studies of the National Academy of Sciences Committee on Biological Effects of Ionizing Radiation (BEIR)

REM is defined as that amount of radiation that produces the same biological effect as one Roentgen of X and gamma radiation.

Properties of X and Gamma Rays

X-rays and gamma rays are a part of electromagnetic radiation.

Figure 2.5 shows the electromagnetic spectrum.

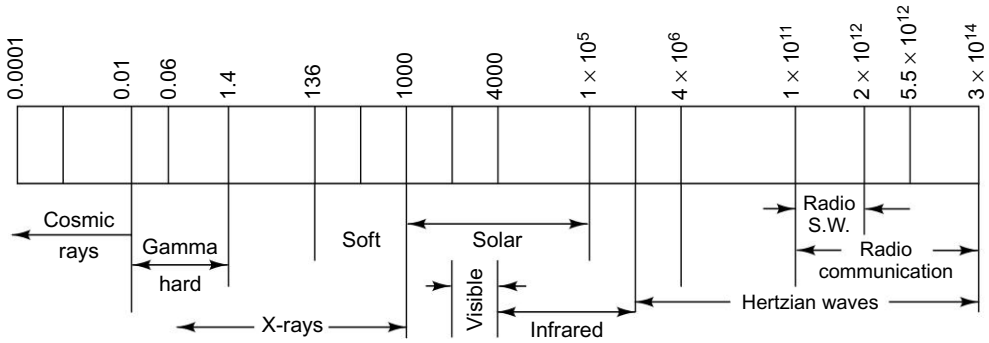


Fig. 2.5 *Electromagnetic Spectrum Chart*

Summary of the properties of X-ray and gamma rays:

- Invisible, pass through space without transference of matter
- Not affected by electric and magnetic fields
- Propagate in a straight line, also exhibit wave properties and are reflected, refracted, diffracted and polarized.
- Transverse electromagnetic waves, velocity of propagation = 3×10^{10} cm/sec
- Capable of ionizing gases and changing the electrical properties of liquids and solids
- Capable of blackening photographic film
- Produce fluorescence and phosphorescence in some substances
- Damage or kill living cells and produce genetic mutation
- Liberate photoelectrons, recoil electrons, electron-positron pair and act photochemically
- Differentially absorbed by matter
- Produce characteristic spectra of chemical elements

Insofar as industrial radiography is concerned, the following properties are relevant:

- Rectilinear propagation
- Differential absorption
- Photographic effect and
- Fluorescence effect

Interaction of X-rays and Gamma Rays with Matter

Penetrating radiation like X-rays or gamma rays passing through a material medium interact with matter in a complex manner. The effect of interaction is attenuation of incident radiation. Attenuation takes place in two ways—absorption and scattering. Figure 2.6 shows complex interaction.

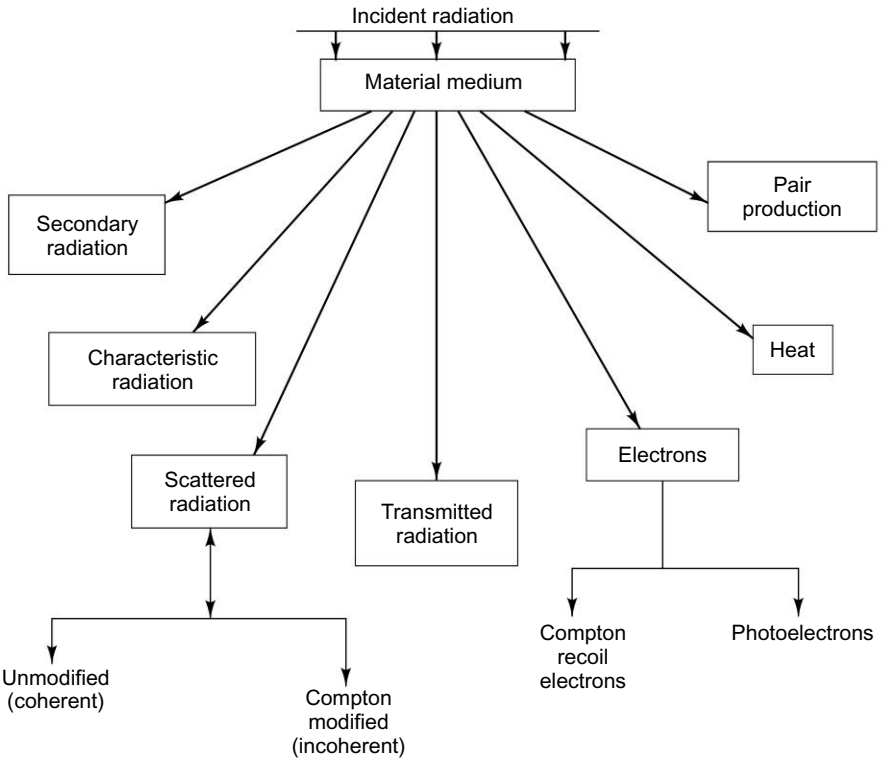


Fig. 2.6 *Interaction of Radiation with Matter*

Attenuation resulting from various interactions is expressed mathematically as:

$I_x = I_0\, e^{-\mu x}$. It is more convenient to express attenuation in terms of per gram of material irradiated. This relationship is expressed as:

$$I_x = I_0\, e^{-\left(\frac{\mu}{p}\right)\rho x}$$ where I_0 = Intensity of incident radiation,

I_x = Reduced intensity of the emergent radiation after traversing a distance X,

μ = A constant called *linear absorption coefficient*, which indicates decrease in intensity per unit length of the material traversed,

ρ = Density of the material and

$\left(\frac{\mu}{p}\right)$ = Mass absorption coefficient

The absorption coefficient remains constant for mono-energetic radiation like gamma rays for a given material; however, it is not so for a spectrum of radiation.

μ is small for radiation of small wavelength (hard radiation) and large for long wavelength (soft radiation).

For chemical compounds or mechanical mixtures (solids or liquids) it is expressed as:

$$\left(\frac{\mu}{p}\right) = a_1\left(\frac{\mu}{\rho^1}\right)_1 + a_2\left(\frac{\mu}{\rho^2}\right)_2 + \ldots.$$

where a_1 and a_2 are the weight fractions of constituents 1, 2, …

Major factors for attenuation of incident X-rays or gamma rays are:

- Photoelectric emission
- Compton scattering
- Pair production

From the viewpoint of industrial radiography, it is of interest to know that:

- Photoelectric emission dominates in the operating voltage range of 200 eV to 100 KeV (low energy range)
- Compton scattering dominates in the operating voltage range of 150 KeV to 300 MeV (medium energy range)
- At higher energy levels, Compton scattering slowly decreases and pair production sets in and dominates above 4 MeV (high-energy range)

2.2 EQUIPMENT

2.2.1 X-ray Equipment

X-ray radiographic equipment consists of:

- X-ray tube
- Arrangement to heat the tube filament to produce electrons
- Arrangement to accelerate electrons to generate high impact energy
- Accessories to rectify, regulate and measure current and voltage and provision to measure X-ray exposure

As mentioned earlier, X-rays are produced inside a highly evacuated glass envelope called an X-ray tube. Features of the X-ray tube are shown in Fig. 2.1. The power supply for heating the filament of the

X-ray tube is provided by a low-tensions transformer. The filament is heated by a current of a few amperes (≃ 5–8 amperes) and at 12–15 Volts.

High voltage applied between the cathode and anode accelerates the electrons produced on the cathode surface and directs them to the target surface. A control unit supplies alternating (unrectified) power to the high-tension transformer. Rectifiers are used to improve the quality and quantity of X-ray output. Most of the industrial X-ray units use either half-wave rectifier systems for low energy portable field units, or full-wave constant potential units for medium energy, heavy-duties fixed/mobile units.

Commercially available X-ray units are classified as:

- Cathode grounded
- Anode grounded

} = Unipolar

- Center tap grounded = Bipolar

Figure 2.7 illustrates unipolar and bipolar units.

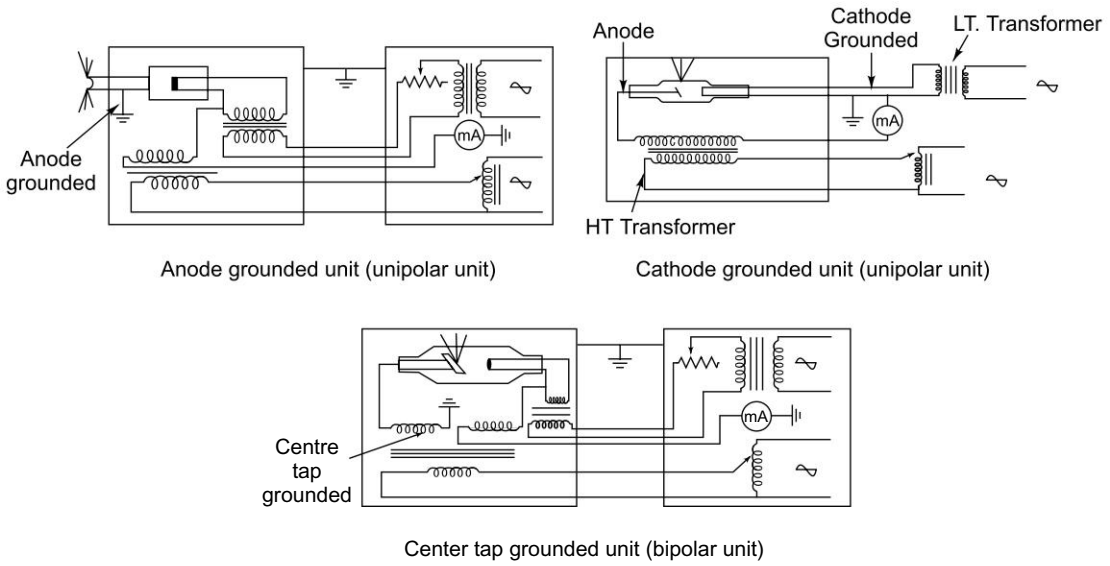


Fig. 2.7 *Unipolar and Bipolar Units*

Unipolar units operate in the range of 50–150 KV with tube current of 5–15 mA. Bipolar units usually operate between 200–400 KV, with tube current of 10–30 mA.

Efficiency of X-ray Units

X-ray generation is an inefficient process. Most of the electrical input energy is converted into heat. Approximately 2% of the input energy is converted into X-rays at about 200–300 KV. Above 2 million Volts, about 50% of the input energy may be converted into X-rays. The output of X-rays from an X-ray unit depends on the design and construction of the X-ray tube, focal spot size, type of rectifier, inherent filtration and voltage output of the high voltage transformer. Table 2.3 gives an idea of X-ray output from commercial X-ray units.

TABLE 2.3 *X-ray output from commercial X-ray units*

Maximum KV	*Focal Spot Size (mm)*	*Tube Current (mA)*	*X-ray Output Roentgens/min at 1 M*
200	2.3 × 2.3	5	4
250	5 × 5	5	20
300	2.3 × 2.3	5	10
350	4 × 4	8	40
400	7 × 6	5	25

As mentioned earlier, most of the input electrical energy is converted into heat. The heat generated at the target surface is so high that it may melt the target unless it is quickly conducted away. For this reason, special arrangements are made for dissipating heat. The most commonly used systems for heat dissipation are:

- Circulation of oil behind the target and into the heat exchanger
- Circulation of water in the tube target extension

Figure 2.8 illustrates such cooling systems.

The effectiveness of cooling system determines the extent to which an X-ray unit can be operated continuously.

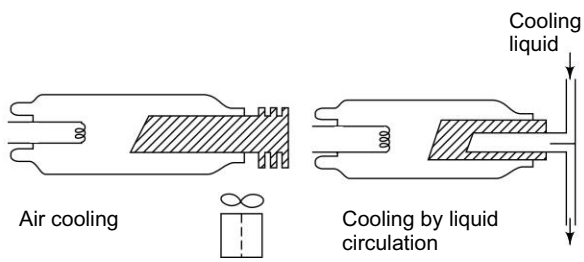


Fig. 2.8 *Usual Methods of Cooling the Tube Target*

2.2.2 Selection of X-ray Units

Practical needs of radiography demand that the following points be given due consideration before selecting a radiographic equipment:

- The degree of penetration must be sufficient to accommodate maximum thickness of material encountered
- The exposure time must be short in order to cope with the volume of work
- The duty cycle (which indicates the extent to which a unit can be operated continuously) must be high enough to keep pace with the speed of production and inspection
- The image quality must be such that all small flaws of interest are revealed, irrespective of their location in the specimen. Smaller focal size gives better image quality
- The manoeuverability—for ease of movement and setting up of exposure
- The reliability of operation

X-ray Fluoroscopic Equipment

When an X-ray impinges on a fluorescent surface like zinc-cadmium sulphide, it produces yellow-green light. This fact is made use of in fluorescent X-ray radiography. The fluorescent radiographic unit consists of:

- A 50–300 KV range X-ray unit
- A radiation leak-proof enclosure

- A suitable window fitted with a fluorescent screen for viewing the radiographic image
- A mechanism for manoeuvering the test object position with respect to the X-ray beam

The arrangement of a fluoroscopic unit is illustrated in Fig. 2.9.

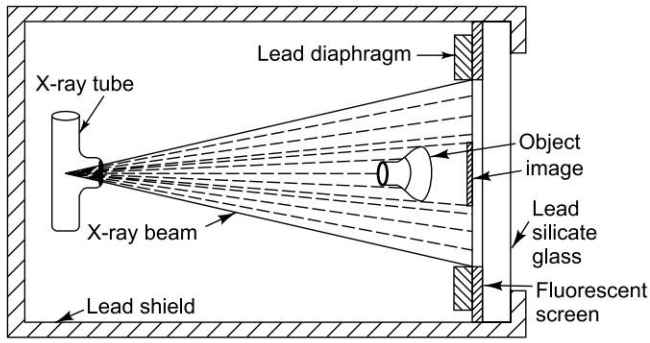


Fig. 2.9 *X-ray Fluoroscopic Unit*

X-rays are differentially absorbed while traversing the object and the emergent beam forms an image of varying brightness on the fluorescent screen. The image is observed in a semi-dark enclosure. The quality of fluorescent pictures is generally poor compared to the quality of pictures obtained in film radiography. Usually a wire type penetrameter sensitivity of 5–10% is achieved as against a normal wire type penetrameter sensitivity of 2% in case of film radiography.

The quality of a fluorescent radiographic image is improved by use of image intensifiers. The principle of an image intensifier is illustrated in Fig. 2.10.

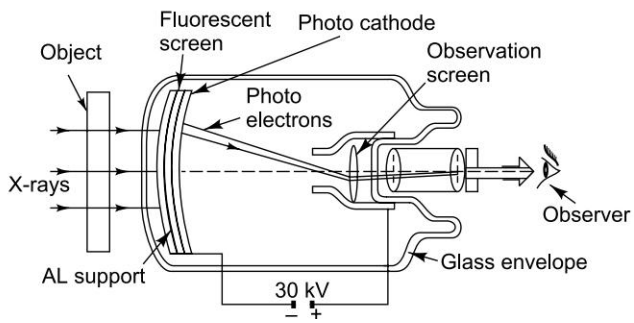


Fig. 2.10 *Image Intensifier*

An image intensifier system has a photo cathode layer next to a fluorescent screen mounted on an aluminum support and the assembly is sealed in an evacuated glass enclosure. The X-rays, emerging from the object, fall on the fluorescent screen and form a visible image of the object. The light from the fluorescent screen falls on the photo cathode layer and causes the emission of electrons. The number of emitted electrons is proportional to the intensity distribution of the X-ray image. Electrons are then accelerated under a potential difference of about 30 KV and focused electrostatically on a fluorescent screen. The brightness of the image on this screen is increased to about 1000 times compared to a conventional fluoroscopic image. The intensified image is observed through a lens system. The improved sensitivity of the radiographic image is almost comparable to film radiographic sensitivity. Figure 2.11 gives a comparative idea of improvement of penetrameter sensitivity as a result of image intensification.

Fluoroscopic X-ray units with image intensification are used in close circuit X-ray television for real time radiography. Figure 2.12 illustrates the basic principle of the system.

X-rays after undergoing differential absorption in the object are converted in to visible light by the fluoroscopic screen, where a radiographic image of the object is formed. This image is collected by an optical lens system and focused on a TV camera tube. The information contained in the fluoroscopic image of the object is converted in to electrical signals. The electrical signals are suitably amplified and converted from analogue to digital image, which is stored, enhanced and viewed on TV monitor.

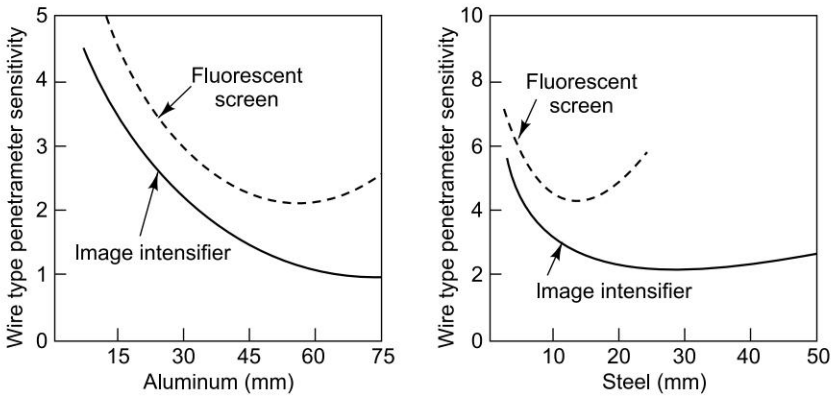


Fig. 2.11 *Relative Sensitivity in Aluminum and Steel after Image Intensification*

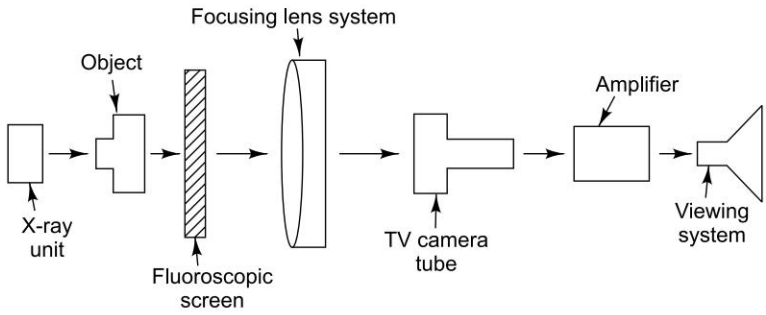


Fig. 2.12 *Principle of Closed Circuit X-ray TV System*

In real time, radiography arrangement of the source, object and image plane is similar to film radiography. Radiographic image is converted in to a digital image through image intensifier, optical lens system between intensifier and video camera. The analogue signal from video camera is digitized, stored, enhanced and displayed on image monitor. Figure 2.12a shows schematic arrangement of the system. The system works in the range of 30 KV to 300 KV. Real time radiographic systems are widely used in Aerospace, Pressure vessel, Automotive, Electronic industries, etc.

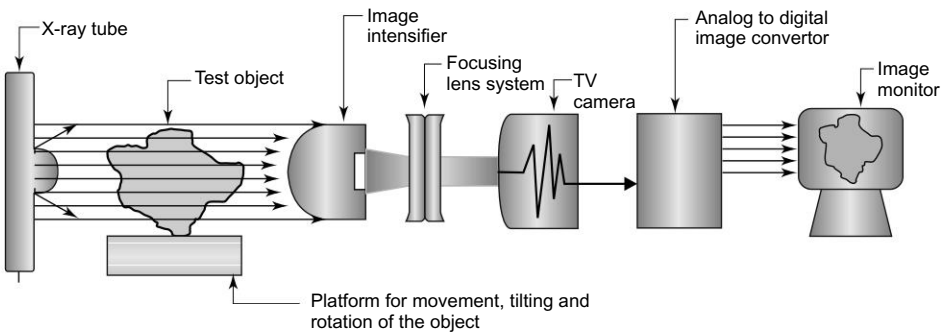


Fig. 2.12a *Schematic Arrangement of Real Time Radiography*

Real time radiographic system has advantage over film radiography in following respects:-

High speed of inspection, image can be viewed simultaneously as the X-rays pass through the test object and the object can be rotated, tilted or moved. Entire object can be inspected in one set up. However, real time radiography is generally less sensitive than film radiography.

In real time radiography, image resolution is influenced by focal size, magnification and performance of imaging system. It is difficult to resolve small defects due to limitations of image intensifiers. Image processing can improve resolution considerably. Normally it is possible to achieve a resolution of 0.1 to 0.06 in film radiography, in real time radiography with image processing, it could be 0.5 to 0.25. Contrast sensitivity of 1 to 2 percent is common in film radiography. In conventional real time radiography, it is 3 to 4 percent. With image processing techniques and micro focal system contrast sensitivity can be improved to 0.5 to 1 percent. Image quality indicators (wire or plaque type) are used in X-ray radiography, in real time radiography line pair gauge is used. This shows how many lines can be discerned in a width of one millimeter. Resolving capacity is indicated as 'lines per mm'.

The system has advantage of presenting clear image at low intensity. The image can be shown as either positive or negative. One or more TV receivers can be arranged in different locations for several viewers to observe and interpret the fluoroscopic image.

Defects usually detected are: cracks, voids, misalignments, lack of fusion/penetration, slag inclusions, seams, shrinkages, forging bursts, laps, cold shuts, etc.

High-energy X-ray Equipment

High-energy X-ray units basically consist of a source of electrons, which is a hot filament, and a means to produce a high electric field to accelerate the electrons. These electrons acquire high energy and are finally made to give up their energy by striking a metal target, where X-rays are produced. Some of the high-energy X-ray units are given in Table 2.4.

Efficiency of X-ray production at higher energies of electrons is approximately 30 – 40% as against 1 – 3% for X-ray units in the 100 – 300 KV range.

Further, a small diameter of X-ray beam gives rise to fine focus (~0.1–0.25 mm). This ensures extreme image sharpness. This helps direct enlargement of the radiographic image of defects.

Scattered Radiation, Filters and Screens

An object in the path of X-rays or gamma rays gives rise to scattered radiation. This may be due to:

- Secondary radiation produced as a result of interaction of the object with impinging radiation.
- Reflection of radiation from surrounding objects like nearby materials, floor walls, film cassettes, etc. Figure 2.13 illustrates this.

TABLE 2.4 *High-energy X-ray units*

High-energy X-ray unit	*Range of Energy Generated*
Vande Graf generator (electrostatic generator)	1 – 6 MeV
Betatron	5 – 100 MeV
Linear accelerator (LINAC)	6 – 50 MeV
Resonant type of transformer	4 MeV

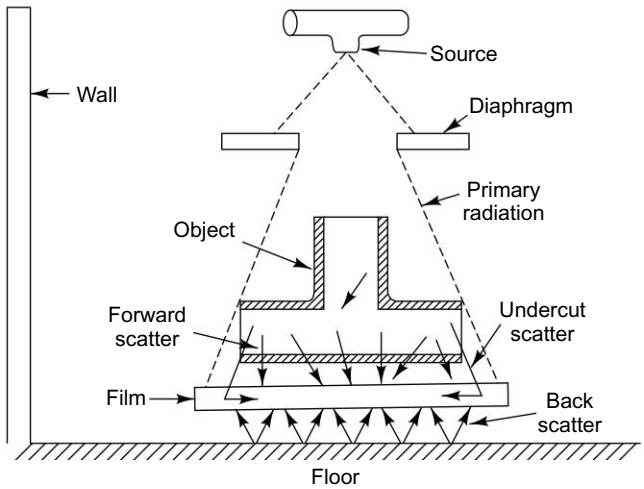


Fig. 2.13 *Effect of Scattering on Image Quality*

Scattered radiation has low energy and less penetration compared to the primary beam. This makes radiographs hazy, with overall fogging, leading to poor image quality. In radiography of thicker objects, the amount of scattered radiation is significantly more intense than the primary radiation reaching the film. Most of the secondary radiation is generated within the specimen and is referred to as internal scatter, forward scatter or transmitted scatter. The undesired effect of scattered radiation on the radiographic image is minimized by keeping a thin lead foil between the object and the film and by collimating the radiation to the area of interest by using a lead diaphragm at the tube port. Another way is to cover the unwanted area of the film by lead sheets. Scattered radiation from all sources can be avoided by sandwiching the film between a pair of lead screens.

Metallic sheets of high atomic number are used as filters to absorb 'soft' radiation (long wavelength) emanating from the tube port and allow comparatively hard radiation (short wavelength) to penetrate the specimen.

The use of filters results in the following advantages:

- Increased contrast around the specimen edge
- Reduced undercut scatter at the edge of thinner sections
- Record wide range of specimen thickness
- Radiograph specimens with advantage where satisfactory masking cannot be done due to complicated geometry

Loss of intensity caused by the addition of filters is compensated either by increasing the time of exposure or the KV.

Generally, filters are made of aluminum, copper or lead. A guideline for the use of filters is given in Table 2.5.

TABLE 2.5 *Filters for various ranges of KV*

KV	*Filter Material*	*Thickness of Filter (mm)*
100 and below	Aluminum	2.0
120–250	Copper	1.0
250–400	Copper	1.0–1.5
	Lead	0.5–1.0

In the million-volt range, the use of a filter at the tube window does not improve radiographic quality. However, filters between the film and the specimen improve image quality for specimens above 40 mm thickness. Below this thickness, filters do not improve image quality. A lead filter of thickness 3.0 mm is found useful in the thickness range of 40–100 mm of steel. Above 100 mm thick steel, a lead filter of 6.0 mm thickness improves image quality.

It is important to use a diaphragm of lead up to 25 mm thickness at the tube window to allow only useful primary beams to reach the area of interest. This avoids heavy scattering from walls or surrounding objects in the exposure room.

Screens

Radiographic film emulsion, when exposed to radiation, absorbs only a small amount of radiation. In order to fully utilize the radiation and enhance the photographic effect, screens are used in combination with films. Screens are of two types: metal foil screens and fluorescent salt screens.

Metal foil screens are usually lead foil screens, consisting of lead foil mounted on cardboard or plastic. These are used in pairs by sandwiching the film between them. One of the screens facing the source side is called the front screen and the other, the back screen—which is placed behind the film.

The main advantages of using lead screens are:

- Enhancement of photographic action on the film by emission of photoelectrons and secondary radiations generated in the lead
- Soft scattered radiation is absorbed more than the primary radiation
- Photographic effect of the primary radiation is intensified at higher energies
- The harmful effect of scattered radiation is reduced, thereby producing greater contrast and clarity in the radiographic image
- Higher intensification reduces exposure time

Besides lead intensifying screens, other metal screens such as copper, tantalum and tungsten screens are also used in high KV X-ray and Co_{60} gamma ray radiography.

Table 2.6 gives screen materials and thickness of front and back screens for various radiations.

Fluorescent intensifying screen or salt screens Fluorescent intensifying screens or salt screens consist of a powdered fluorescent material, such as calcium tungstate or barium lead sulfate, of which a thin uniform layer is spread with a suitable binder on a cardboard or a plastic support. The fluorescent material emits visible or ultraviolet light when exposed to X-rays or gamma rays. The intensity of emitted light depends on the intensity of incident radiation. The main advantage of using fluorescent salt screens is to drastically reduce the exposure time since the intensification factor is very high compared to lead intensifying screens. However, the intensification factor diminishes both at lower as well as very

TABLE 2.6 *Screen material and recommended thickness*

Radiation	*Screen Material*	*Front Screen Thickness (mm)*	*Back Screen Thickness (mm)*
X-rays			
120 KV	Lead	0.02–0.04	0.1
120–250 KV	Lead	0.05–0.1	0.1
250–400 KV	Lead	0.1	0.1
1000 KV	Lead	1.5–2.0	1.0
5–10 MeV	Copper	1.5–2.0	1.5–2.0
15–30 MeV	Tantalum/Tungsten	1.0–1.5	Non
Gamma rays			
Ir_{192}	Lead	0.1	0.1–0.15
Cs_{137}	Lead	0.1	0.1–0.15
Co_{60}	Copper*	0.5–2.0	0.25–1.0

* Copper screens produce better radiographs than lead screens but require a longer exposure approximately by a factor of 2.

high energies. The use of these screens is limited in the field of industrial radiography because they produce poor definition and grainy images.

Fluorescent screens are not used in gamma radiography, as intensification is poor with long exposures, usually common in gamma ray radiography.

Foreign particles—dirt, dust, etc.—should be prevented from accumulating between the screen and the film, as they tend to cast their shadow on the film. Further, the screen should not be exposed to the primary beam and should be stored away from chemicals and other sources of contamination.

2.2.3 Gamma Ray Equipment

Gamma ray equipment consists of an isotopic source pencil and a container for positioning the source pencil. Figure 2.14 shows the arrangement.

The container is designed for safe handling of the source and for easy portability. The isotopic sources are usually in the form of a cylinder of diameter equal to its length. These are encapsulated in a container made of steel, aluminum or an alloy of magnesium and aluminum. The size of the source ranges from 0.4 mm to 6 mm. The size of most of the gamma ray sources for routine radiography

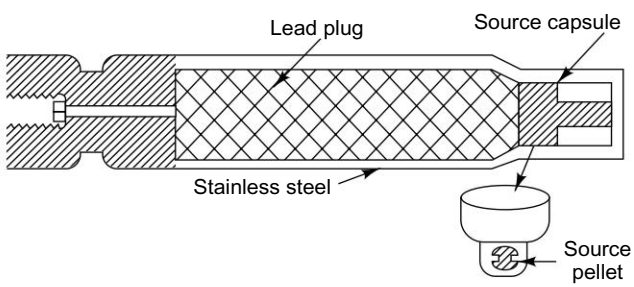


Fig. 2.14 *Gamma Ray Source Pencil*

is approximately 3 mm × 3 mm. This size is comparable to the effective focal spot size of an X-ray tube. The source capsule is contained in the source pencil, made of stainless steel. The source pencil is placed at one end of the container and the other end is threaded for positioning the pencil inside the container with the help of a manipulator rod.

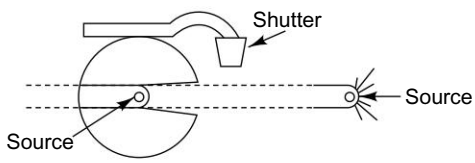
Source pencil requirement:

(i) Not more than 1% beta radiation is allowed to be transmitted through the source pencil
(ii) The material of the source pencil should be corrosion resistant, and should not react chemically with the radiation source
(iii) The source pencil should be leak-proof
(iv) The source pencil should be as small as possible
(v) All radiation sources should be sealed and marked for easy identification

Source camera:

The radiographic container (camera) is designed in such a way that there is no leakage of radiation above the permissible level when not in use. The camera is usually made of lead or depleted uranium. Depleted uranium makes it lighter. Further, the camera is designed to facilitate easy loading, exchange of the source and easy opening and closing of shutters. There are four types of gamma ray cameras as shown in Figs 2.15 to 2.18.

Some cameras have the mechanism of lifting the source to position it as required, in the case of radiography of pipeline welding. Here, the source is attached to the lead backing, which in turn is connected to the camera-opening handle. A low strength source is used in this camera.



The shutter is opened from the rear with the help of a hinge mechanism. It can be positioned for panoramic exposure with the help of a long handle. For panoramic exposure, source strength is not more than 8 Curie of Ir^{192}

Fig. 2.15 *Gamma Ray Camera with Conical Shutter*

High-strength sources are kept in stationary cameras, which have a remote control mechanism for rotating and bringing out the source to the surface of the camera for exposure.

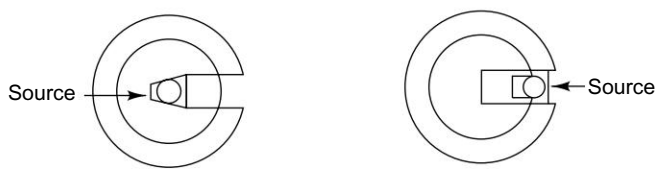


Fig. 2.16 *Gamma Ray Camera with Source Rotating Mechanism*

High energy, high strength sources employ cameras with source attached to a flexible cable. In storage, the source is in the container. The source capsule could be extended to the required position through an extension tube with the help of a flexible cable attached to a control box. This cable can be controlled either manually or electrically. The extension rod runs to a length of 20 – 25 meters. The flexible cable operation method ensures safe handling of the source with adequate distance shielding.

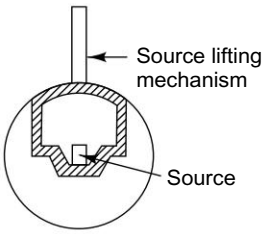


Fig. 2.17 *Gamma Ray Camera with Source Lifting Mechanism*

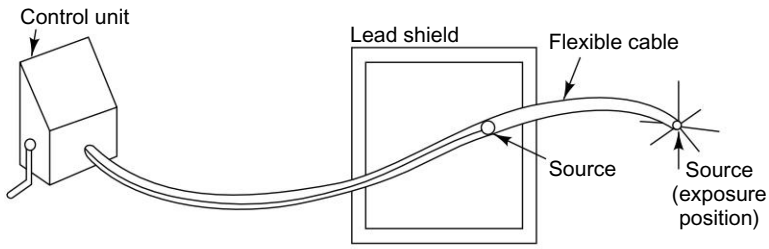


Fig. 2.18 *Gamma Ray Camera with Remote Handling Mechanism*

2.3 General Radiographic Procedure

Radiography is essentially a technique of projecting a three-dimensional object on a plane, utilizing a few of the properties of X-rays, gamma rays or any other penetration radiation. The properties used are:

- Rectilinear propagation
- Differential absorption
- Photographic or fluorescence effects

The projected image of the object is called a 'radiograph' and the process of obtaining the radiographic image and evaluating its contents is called 'radiography'.

The essential requirements for producing a radiograph are:

- A source of radiation
- Object to be examined
- Recording medium and
- Processing chemicals

In this section, the radiographic process using X-rays and gamma rays as the source of radiation and films as the recording medium is discussed.

Irrespective of the type of component/assembly to be radiographed, the following steps are followed during radiography:

- Surface preparation
- Selection of radiation source depending on density and thickness of the object
- Optimizing exposure parameters and usage of exposure charts
- Selection and processing of film
- Ensuring appropriate radiographic sensitivity by using Image Quality Indicators (IQI)
- Keeping image unsharpness to as low a value as possible

2.3.1 Surface Preparation

Gross imperfection of the surface needs to be removed, as it creates confusion in the interpretation of internal defects. In case of castings, it is necessary to remove gates, risers, deep fettling marks and adhered sand from the surface. In case of welding, deep surface cavities, slag and any other surface blemishes that may hamper interpretation of internal defects should be removed. The surface of raw casting or welding need not have smooth surface finish. Sand particles adhering to the surface and

particles that have gone to corners and other accessible cavities should be thoroughly cleaned by wire brush. Parts/assemblies should be free from oil, grease or dirt, etc. as these may spoil the film cassette and holders.

2.3.2 Selection of Radiation Source

Selection of the radiation source depends on the thickness and material density of the object to be radiographed. Generally, steel of 50 mm thickness or equivalent thickness of light alloys are examined by X-ray equipment up to 400 KV capacity. For higher thicknesses, gamma ray isotopes such as Ir^{192} or Cobalt-60 are used. Refer to Table 2.1. For field radiography of weldments and assemblies, portable light-weight X-ray equipment is used. However, in a situation where positioning the X-ray tube head is found impracticable due to limited space, portable gamma ray isotopes are used.

2.3.3 Exposure Parameter and Usage of Exposure Charts

Exposure parameter implies optimization of all the factors that contribute to the formation of a radiographic image. In this respect, the following factors are of importance:

- Optimization of beam energy, radiation output, time for which radiation impinges on the object, distance of the object from the source of radiation
- Orientation of the object with respect to the axis of the radiation beam
- Image recording medium, e.g. films/fluorescent screens
- Dimensions of the source of radiation (e.g. focal spot size or capsule size)

Exposure parameters for a given component of known composition are determined with the help of what is known as an 'Exposure chart'. An exposure chart is a graphical relationship between material thickness, beam energy (KV) and quantity of radiation (mA × time of exposure). Usually X-ray equipment manufacturers supply exposure charts for various thicknesses of steel. Suitable corrections are made while using other materials. Normally, exposure charts are prepared for a specific X-ray machine, because quality and radiation output are not the same for all types of machines for the same operating KV and mA.

Therefore, exposure charts prepared for a specific machine are used as a guide for developing correct exposure parameters. In the absence of a readymade exposure chart, one is prepared as discussed next.

A step wedge, as shown in Fig. 2.19 of selected material, with known thickness at each step, is exposed on a film.

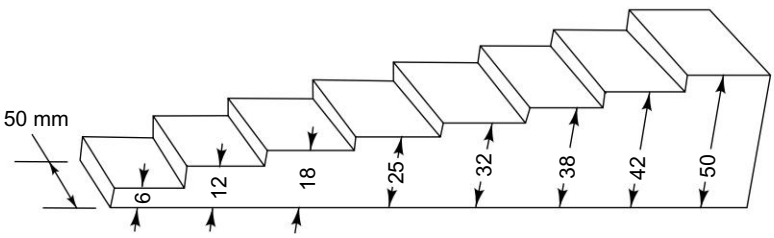


Fig. 2.19 *Step Wedge*

To start with, each step is exposed at a low KV. with arbitrary exposure (mA × minutes). This exercise is repeated for different mA × minutes, with the same KV The same step wedge is exposed

again at different KV for different values of mA × minutes. After exposure, all the films are developed in standard chemicals under the same conditions. The radiographs are examined and the density is measured with a micro-densitometer. The exposure corresponding to an acceptable density (say 2) for a step of particular thickness is identified. This procedure is repeated and exposures corresponding to the same density 2 are identified for different step thicknesses. A table is then prepared for each setting of KV and mA × minutes, required to produce the density 2 for different thicknesses. With this data, a graph is plotted with thickness on the abscissa and mA × minute on the ordinate for different KV. It is preferable to draw the chart on a semi-log graph so that exposure values assume small numbers and the size of the chart is reduced. The exposure chart thus generated is strictly true for the machine used, the type of film employed and the material examined. Any change in these parameters may require some variation and correction to achieve the same density. Figure 2.20 shows a typical exposure chart.

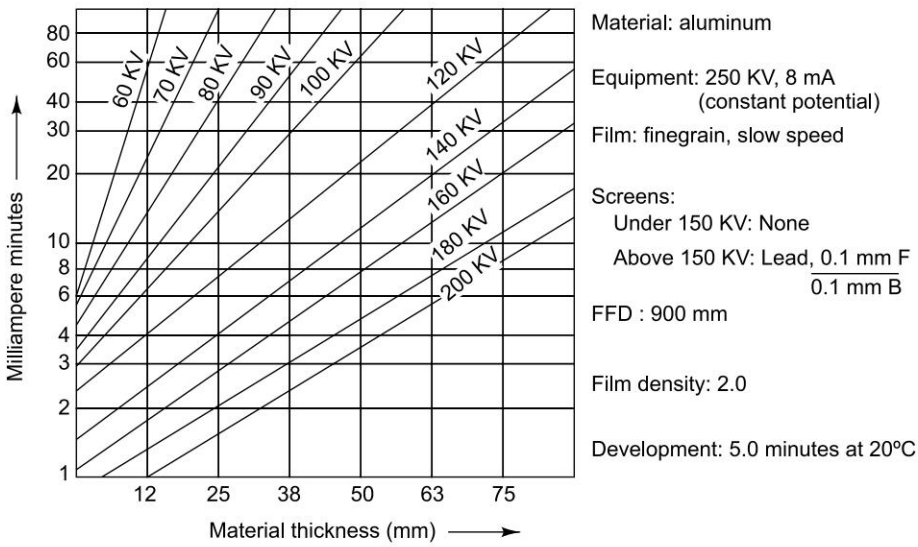


Fig. 2.20 *Exposure Chart*

If, for some reason, a situation warrants changes in mA, time or distance, actual exposure can be calculated using the following relationships:

1. $\frac{M_1}{M_2} = \frac{D_1^2}{D_2^2}$ where M_1 and M_2 are milliamperes corresponding to distance D_1 and D_2 required to produce the same film density
2. $\frac{T_1}{T_2} = \frac{D_1^2}{D_2^2}$ where T_1 and T_2 are exposure times corresponding to distances D_1 and D_2 required to produce the same film density
3. The photographic effect remains same so long as the product of mA and time remains constant. This is commonly referred to as the 'Reciprocity law'. This is expressed as:
   $M_1T_1 = M_2T_2 = \text{Const.}$
4. The intensity of X and Gamma radiation varies inversely as the square of the distance between the source and the object. To adjust the effect of the variation of intensity, we use the inverse square law, expressed mathematically as:

$$\frac{I_1}{I_2} = \frac{D_2^2}{D_1^2} \text{ or } I_2 = I_1 \frac{D_1^2}{D_2^2} \text{ where } I_1 \text{ and } I_2 \text{ are intensities at distances } D_1 \text{ and } D_2$$

Normally, exposure charts are drawn for steels or aluminum. It is possible to use these charts for other materials as well, if the thickness of the materials is converted to equivalent thickness of material for which the exposure chart is available.

While converting the thicknesses to equivalent thickness of material for which exposure chart is available (say steel), it needs to be appreciated that X-ray absorption varies according to the atomic weight of elements present in absorbing materials in the KV range 50 – 150. At lower radiation energy, the absorption is sensitive to the atomic number of the absorber. However, at higher energies, the absorption is mainly a function of the density of the absorber material. Above 1 MeV radiation energy, steel equivalent thickness is obtained by multiplying the absorber thickness by the ratio of densities of the absorber material and steel. A guideline for radiographic equivalent factors is given in Table 2.7.

TABLE 2.7 *Approximate equivalent factors for materials*

Metal	***Approximate Radiograph Equivalence Factors***										
	Energy Level										
	100 KV	***150 KV***	***220 KV***	***250 KV***	***400 KV***	***1 MeV***	***2 MeV***	***4-25 MeV***	***Ir^{192}***	***Co^{60}***	***Cs^{137}***
Magnesium	0.05	0.05	0.08								
Aluminum	0.08	0.12	0.18						0.35	0.35	0.35
Aluminum alloy	0.10	0.14	0.18						0.35	0.35	0.35
Titanium		0.54	0.54		0.71	0.9	0.9	0.9	0.9	0.9	
Iron/all steels	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Copper	1.5	1.6	1.4	1.4	1.4	1.1	1.1	1.2	1.1	1.1	1.1
Zinc		1.4	1.3		1.3			1.2	1.1	1.0	1.0
Brass		1.4	1.3		1.3	1.2	1.1	1.0	1.1	1.0	1.1
Inconel X		1.4	1.3		1.3	1.3	1.3	1.3	1.3	1.3	1.3
Monel	1.7			1.2							
Zirconium	2.4	2.3	2.0	1.7	1.5	1.0	1.0	1.0	1.2	1.0	
Lead	14.0	14.0	12.0			5.0	2.5	2.7	4.0	2.3	2.0
Hafnium			14.0	12.0	9.0	3.0					
Uranium			20.0	16.0	12.0	4.0		3.9	12.6	3.4	

Uniform thickness of material can be radiographed with the help of an established exposure chart. However, specimens with varying thicknesses are often required to be radiographed.

If thickness variation is large, separate exposures have to be taken. However, if thickness variation is not large, it is possible to record different thicknesses in one exposure. This involves the use of different speeds of film together in one exposure. The smallest section is recorded on the slowest film; the thickest section, on the fastest film and intermediate thickness is recorded on the medium-fast film. In this case, exposure is adjusted for the thickest section and the fastest film. Usually this results in acceptable densities on all films in the areas of interest.

2.3.4 Radiography Using Gamma Ray Isotopes

The principle of image formation remains same irrespective of type of the radiation source. Table 2.8 provides a guideline for selection of gamma ray sources for radiography.

TABLE 2.8 *Guideline for selection of gamma ray sources for radiography*

Source	*Half-life*	*Energy (MeV)*	*Specific Emission REM from 1 Curie*	*Thickness (mm)*	
				Steel	*Light alloy*
Cobalt 60	5.26 yrs	1.4	1.3	230	125–375
Cesium 137	30 yrs	0.66	0.31	75	75 – 300
Iridium 192	70 days	0.5	0.5	75	25 – 200
Thulium 170	127 days	0.084	0.0025	Up to 12.5	Up to 37.5

Having selected the source, the next step is to determine the exposure parameters. Established exposure charts are used for this purpose. A typical exposure chart would show 'Curie × minute' on the *y*-axis and thickness on the *x*-axis for different film densities. This is true for a fixed 'source-film-distance', a particular type of film and for a specific material (usually steel).

In the absence of a gamma ray exposure chart, the following formula may be used for determining exposure time in hours:

$$\text{Exposure time} = \frac{(d \times D^2 \times 2^n)}{(S \times Rd)}$$

where d = dose in Roentgen required to produce desired density
n = object thickness/half value layer
Rd = RHM per Curie
S = source strength in Curie
D = source to film distance in meters

In gamma radiography, it is necessary to use a lead intensifying screen to improve the image quality. The thickness of the front screen should not be less than 0.1 mm and that of the back screen, 0.1 – 0.15 mm. In general, the minimum source to film distance should not be less than 8 times the object thickness and geometric unsharpness should be maintained in the range of 0.25 – 0.1 mm.

2.3.5 Radiographic Films

Radiographic films contain an emulsion in which fine grains of silver halide are suspended. These grains are sensitized when exposed to radiation and a change occurs in their physical structure. Radiation, after passing through an object, is allowed to fall on the film, where a latent image is formed. When the exposed film is developed using the necessary processing chemicals, the latent image transforms into a visible image. This is the radiographic image of the object. The exposed area of the film turns dark, while the unexposed area becomes transparent. The varying amounts of radiation received on different areas of the film results in varying degrees of darkening. The film darkness is referred to as 'film density'. The darker the image, the higher is the film density. The relative difference of film densities between different areas on the radiograph is referred to as 'contrast'. Variation in density on the radiograph may be either due to variation of geometry, in-homogeneity or presence of discontinuity in the specimen.

The structure of radiographic films is shown in Fig. 2.21. It consists of seven layers. The base is the transparent, thickest layer made of cellulose acetate. This base has high transparency, toughness and flexibility. Some manufacturers use polyester as base. A bonding layer contains a mixture of gelatin and cellulose-ester solvents.

This layer is coated on both sides of the base. The sensitive emulsion consists of minute crystals of silver bromide, suspended in gelatin. This layer is coated on both sides of the bonding layer. An anti-abrasion layer consisting of only gelatin is coated on the sensitive emulsion layer, for protection from physical damage. The emulsions are sensitive to light, X-rays and gamma rays. However, the films are relatively insensitive to red or yellow light of low intensity.

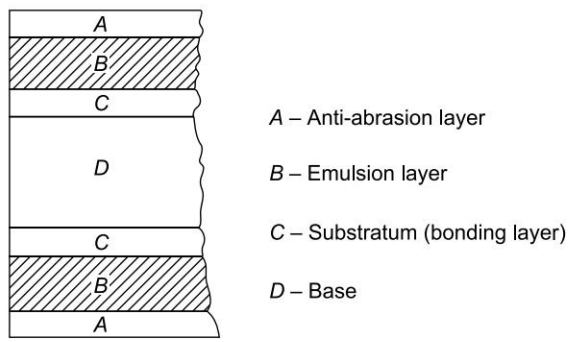


Fig. 2.21 *Structure of a Radiographic Film*

Film Characteristics

A film is characterized by its characteristic curve. This curve gives the relationship between film density, plotted on the *y*-axis, and log relative exposure, plotted on the *x*-axis. The curve is also referred to as D-log *E* curve, HD curve and densitometry curve. Characteristic curves provide useful information related to speed and contrast of a given film. This helps to select the appropriate film for a given radiographic work. Important parameters of interest are the speed and the contrast of the film.

Speed denotes the sensitivity of the film to radiation. When exposed to the same quantity of radiation, a fast film becomes darker (high density) than a slow film. All films show a variation in density for a given change in exposure. A film that shows large density variation for a given change in exposure is said to have 'high contrast'. As an example, characteristic curves of two films *A* and *B* are given in Fig. 2.22. It is seen that film *A* is a high contrast film compared to *B*. For film *A*, at higher exposures, the density difference is much higher compared to film *B* for the same degree of exposure. However, high contrast films produce high-density radiographs, which require high intensity illuminators to view the radiograph.

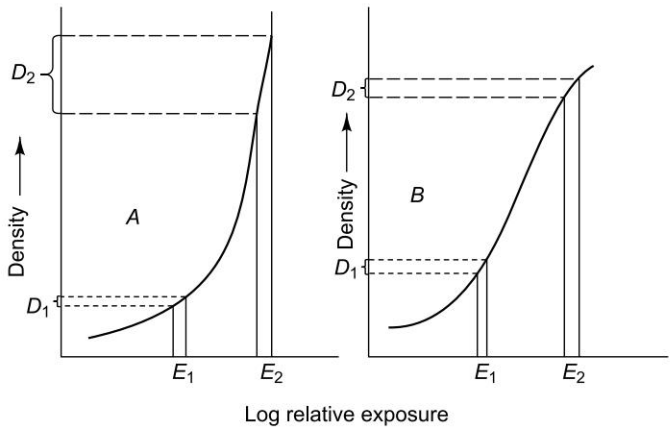


Fig. 2.22 *Characteristics Curve of X-ray Film*

Commercially available films are of the following types:

- Single coated, very low speed, very fine grain and high contrast type. These films are used to detect fine details
- Double coated, low speed, high contrast, fine grain type. These films are used primarily for radiography of light alloys
- Double coated, medium speed, high contrast fine grain type. These films are used for radiography of thick sections, steel welds and castings
- Double coated, high speed, medium contrast, medium grain type. These films are used with fluorescent screens. Table 2.9 gives approximate equivalents of commercially available films

TABLE 2.9 *Approximate equivalents of radiographic films*

Trade Name	***Equivalent Type***				
	Fine Grain, Low Speed		***Fine Grain, Medium Speed***		***Medium Grain, High Speed***
Agfa-Gevaert structurix	D_2	D_4	D_5	D_7	D_{10}
Kodak industrex	R*	M	T	AA	–
Dupont cronex	NDT-45	NDT-55	NDT-65	NDT-70	NDT-91

* Available both as single coated and double coated emulsion.

Selection of Films

Selection of film for a given radiographic requirement is guided by the nature and size of the flaw of interest, and the thickness and material density of the object to be radiographed. For light alloys like aluminum, magnesium and titanium of thin sections, it is desirable to use slow, fine grain film to ensure maximum resolution. For thick sections (25 mm and above) of light alloys and thick ferrous alloys (5–20 mm), fine grain to medium grain films can be used to achieve normal radiographic sensitivity. Above this thickness, fast film can be used. However, the use of fast films leads to poor flaw sensitivity.

2.3.6 Radiographic Sensitivity and Image Quality Indicators (IQI)

The effectiveness of a radiographic technique to bring out the smallest details in a given thickness of an object is referred to as 'radiographic sensitivity'. It is measured as a percentage ratio of the smallest size of an artificially produced defect shown on the radiograph to the thickness of the object under examination. It is mathematically expressed as:

$$\text{Radiographic sensitivity} = \frac{\Delta t}{t} \times 100$$

where Δt = smallest size of an artificial defect
t = thickness of the object

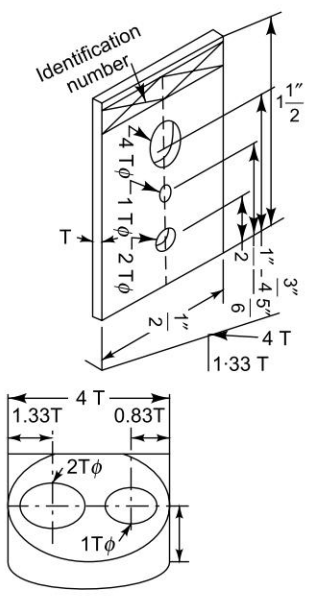
The smaller the numerical value of sensitivity, the better is the radiographic sensitivity.

Artificial defects are made in the form of holes, steps or wires of various dimensions. These are called Image Quality Indicators or 'penetrameters'. During radiography, Image Quality Indicators are kept on the object and their radiographic image is recorded for purposes of evaluating radiographic sensitivity.

Image Quality Indicators are made of materials similar to that of the object being examined. These are available as thin plaques, step wedges or wires.

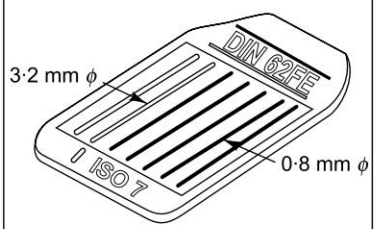
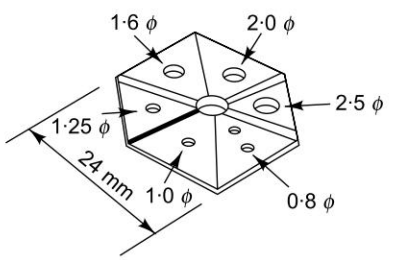
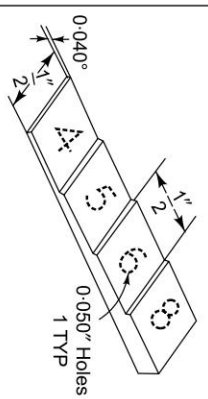
Most commonly used IQI are of American, German, French or British origin. A short description of IQI is given in Table 2.10.

TABLE 2.10 *Description of IQI*

Type of IQI	*Brief Description*
American-plaque type 	These are available as thin plaques of material, having a thickness equal to 2% of the thickness of the material being radiographed. The plaque has three holes of diameters 1t, 2t and 4t, where t is the thickness of the plaque. Adequacy of contrast is determined by the image of the outline of the plaque; the visibility of the holes determines the sharpness of the image. Visibility of the smallest hole on the plaque is a measure of high image sharpness. The thickness of IQI ranges from 005" (≃0.125 mm) to 0.15" (≃3.75 mm). Normally sensitivity is expressed in the form '2-2T level' or '2-1T level'. '2-2T' means that IQI thickness is 2% of the object thickness and 2T refers to the visibility of the hole whose diameter is twice the thickness of the IQI.

(*Contd*)

(*Table 2.10 Contd*)

<table>
<tr><th>Type of IQI</th><th>Brief Description</th></tr>
<tr><td>German-wire type
 
</td><td>This type of IQI consists of equidistant parallel wires of various diameters. There are three series of IQI containing seven wires, 5 mm apart and mounted between two thin sheets of low X-ray absorption. The first series consists of wire nos. 1 to 7 the second consists of wire nos. 6 to 12 and the third series consists of wire nos. 10 to 16. Wire numbers and their diameters are given here:
<table>
<tr><th>Wire no.</th><th>Diameter (mm)</th><th>Wire no.</th><th>Diameter (mm)</th></tr>
<tr><td>1</td><td>3.20</td><td>9</td><td>0.50</td></tr>
<tr><td>2</td><td>2.50</td><td>10</td><td>0.40</td></tr>
<tr><td>3</td><td>2.00</td><td>11</td><td>0.32</td></tr>
<tr><td>4</td><td>1.60</td><td>12</td><td>0.25</td></tr>
<tr><td>5</td><td>1.25</td><td>13</td><td>0.20</td></tr>
<tr><td>6</td><td>1.00</td><td>14</td><td>0.16</td></tr>
<tr><td>7</td><td>0.80</td><td>15</td><td>0.125</td></tr>
<tr><td>8</td><td>0.63</td><td>16</td><td>0.10</td></tr>
</table></td></tr>
<tr><td colspan="2">Visibility of the thinnest wire on the radiograph, without any ambiguity, is a measure of achieved sensitivity. The sensitivity figure is calculated from the relationship:
Radiographic sensitivity (%) = $\left(\frac{\text{Diameter of thinnest wire visible}}{\text{Thickness of the object under IQI}}\right) \times 100$</td></tr>
<tr><td>French-step and hole type
 
</td><td>This type of IQI has a rectangular step wedge with square steps or a hexagonal step wedge with triangular steps. Steps are drilled with one or more holes of diameter equal to the thickness of the step. Steps with thickness of less than 0.8 mm are drilled with two holes of the same diameter. The thickness of steps increases in geometric progression. A typical hexagonal type IQI is shown in the figure. The image quality is determined by the visibility index. The visibility index N is given by the formula $N = (a-b)$, where a is the number of holes visible on the radiograph and b is the number of holes that would be visible in all steps having a thickness greater than or equal to 5% of the thickness of the object under examination. The value of N can be positive, zero or negative. The sensitivity is better as the positive value of N increases.</td></tr>
<tr><td>British welding research association IQI
 
</td><td>This is a step type of IQI where each step is 1/2" square and contains small holes forming a number indicative of thickness of steps. Two types of IQI are in use, one with thickness of 0.005", 0.010", 0.020", 0.030" and 0.040" and holes of 1/40" diameter and the other from 0.040" to 0.080" thick in increments of 0.010", with holes of 1/20" diameter.
The visibility of all the holes in a specified step determines the sensitivity.</td></tr>
</table>

The IQIs must be placed on the specimen facing the source. The placing of IQIs on critical areas, where it is likely to mask fine discontinuity and where it is not practicable to place the IQI on a component surface for want of space or due to the intricate shape of the component, the IQI is placed on a separate block of the same material and thickness as the component under examination. On specimens of varying thicknesses, more than one IQI is used at the same time on different thicknesses where a single exposure is required.

The purpose of using an IQI is to judge the quality of a radiograph for a given setup. The sensitivity values are not the same for different types of IQIs for a given thickness. Therefore, it is necessary that wherever IQI sensitivity is specified, the type of IQI and the specimen thickness should also be mentioned.

Further, IQI sensitivity is not the true flaw sensitivity, although it may indicate, approximately, the flaw sensitivity under ideal conditions of flaw orientation with respect to the beam axis. IQI sensitivity may differ from person to person, for the same exposure, depending on their visual acuity.

The relationship between the true size and shape of the flaw and its projected radiographic image is affected significantly by the orientation of the flaw with respect to the beam axis, source size, source-to-film and film-to-object distance, shape, surface condition, type of the film and the radiation energy.

2.3.7 Image Un-sharpness

It is desirable that a radiographic image on a film has a clear demarcation between two different densities, without distortion. However, in practice, it is rarely possible to get an image without some amount of un-sharpness. This un-sharpness is the result of:

- Finite size of radiation source/focal spot size
- Thickness, shape and surface condition of the object
- Distance between source and object and between object and film; and
- Type of X-ray film.

In practice, un-sharpness is reduced to a minimum acceptable level by optimizing the geometrical variables and using a fine grain film.

It is clear that un-sharpness is caused due to geometrical factors as well as quality of film.

In so far as geometrical factors of un-sharpness are concerned, the following illustrations show the variations in geometrical un-sharpness under different conditions.

In practice, some amount of geometric un-sharpness is unavoidable. Efforts are made to reduce it to a minimum. It is mathematically expressed as:

$$U_g = f \frac{t}{D}$$

where f = source size
D = source-to-object distance
t = object-to-film distance

For industrial radiographs, the acceptable geometric un-sharpness is in the range of 0.2 to 1.0 mm.

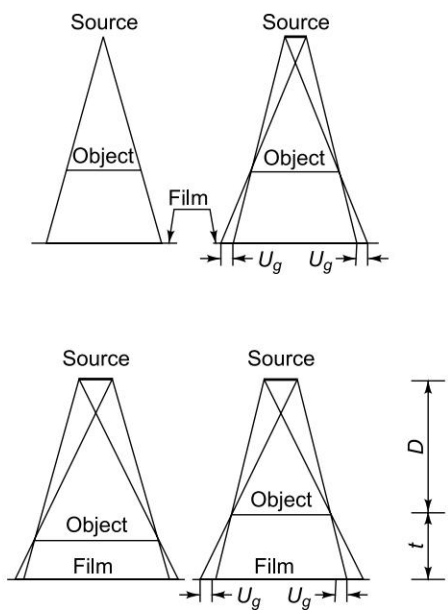


Fig. 2.23 *Geometric Un-sharpness (U_g)*

Film un-sharpness, also called *inherent un-sharpness,* is due to a fuzzy image edge, which increases with increase in the incident radiation energy. Other factors that contribute to film un-sharpness include scattered radiation and characteristic X-rays reaching the film emulsion.

2.3.8 Reading and Interpretation of Radiographs

The purpose of reading and interpreting a radiograph is to identify the discontinuities on the radiograph and correlate them with their appearance and location in the actual component, with a view to assessing the serviceability of the component.

Film Viewing Conditions

Films are viewed in a semi-dark enclosure. The interpreter needs to get adapted to subdued lighting. Extraneous light in the viewing room and direct light from the illuminator should be avoided. Further, it is important that the interpreter has good eyesight, to be able to see the smallest detail on the radiograph. Any deficiency in vision should be corrected by using glasses certified by an ophthalmologist. Another important requirement for viewing a radiograph is appropriateness of light intensity from the illuminator, which depends upon the optical density of the radiograph.

In industrial radiographs, the normal working density varies from 1.5 to 3. Therefore, the illumination requirement is to provide sufficient light of an intensity to read this range of density. Thus, the requirements of illumination for viewing a radiograph are critical. Failure to use the correct illumination may result in missing fine details that have been brought out on the radiograph by adopting the best exposure techniques. The International Institute of Welding has made recommendations for illumination brightness as follows:

TABLE 2.11 *Recommended illuminator brightness for radiographic densities*

Radiographic Density	*Required Illuminator Brightness*
1.0	300 candelas/m^2
2.0	3,000 candelas/m^2
4.0	30,000 candelas/m^2

Commercially available illuminators fitted with fluorescent tubes are useful to read densities up to 1.8. Small illuminators are provided with ordinary electric bulbs, which produce heat when the light is ‘on’. A glass baffle is introduced between the light source and the illuminator screen to avoid excess heat reaching the screen and the film. Illuminator screens are commonly made of translucent milky white Perspex sheets. For high-density radiographs (density 2–4), high-intensity illuminators are used. This type of illuminator is provided with a reflector-type 500-watt bulb, with a regulator to adjust the intensity to any desired level. Fans and ventilators are provided to remove heat; an iris or a diaphragm is provided for masking unwanted areas.

Continuous viewing beyond a certain duration causes eye fatigue. Normally, an interpreter should not view the radiographs continuously for more than 90 minutes. However, after a break of 30 minutes, viewing can be continued.

Qualification of Finished Radiographs

Radiographs are considered acceptable if they are produced as per established exposure techniques. In the absence of an established radiographic exposure technique, the radiograph is qualified based on the adequacy of film type, density and IQI sensitivity. Guidelines for the selection of films has been discussed earlier. The range of density 1.5 to 3.0 and IQI sensitivity of at least 2% are considered acceptable.

Further, the radiograph must be free of any spurious indications. Radiographs showing artifacts in critical areas are not acceptable and should be rejected.

If a radiograph is found acceptable, the next step is to verify the following:

1. Whether the radiograph pertains to the actual component being examined.
2. If more than one exposure is involved for a component, each zone of the component must be correlated and confirmed about coverage and identification.

Identification and Evaluation of Discontinuities

The radiographic image of a discontinuity in a component shows a variation of density compared to its surroundings. The density may be higher or lower, depending on the nature of the discontinuity. A void in a component results in a darker image (high optical density) than its surroundings. A foreign object of higher material density causes a lighter image (low optical density) on the radiograph. However, it should be realized that if the density of an entrapped inclusion in a component is the same as that of the component, such an inclusion might not be revealed on the radiograph. Further, radiography is not an effective tool for detecting planer type of discontinuities.

The discontinuity may be on the surface of the component or inside it. Surface imperfection such as rough surface, pits, flash lines, excess material, tool mark, etc. should be correlated with radiographic indications. Other defects could be due to manufacturing process and material characteristics.

An understanding of the material and the manufacturing process goes a long way in correlating radiographic indication with the exact nature and origin of the discontinuity. International agencies such as ASTM, IIW, BS, etc. have published reference radiographs for various radiographic indications in different materials. Each indication on the radiograph is due to a specific mechanical or metallurgical process. By establishing the identity of indication by comparison with reference standards, a radiographer should be able to identify the cause of occurrence of the discontinuity.

Evaluation of defects is done by comparing the test object radiograph with the known standard reference radiographs having different degrees of each defect. The limit of acceptance/rejection, however, is based on the service application of the component, keeping in view the service environment and the design stipulated mechanical property requirement. Often, it may be necessary to generate a defect-property data for this purpose. A guideline on the acceptance of various defects is given in the section 'Radiographic Technique and Acceptance Standard.'

Interpretation of Casting Radiographs

Castings are made of different metals and by various methods. Sand molded castings often have more surface irregularities than casting produced by metal mold and investment methods. Knowledge of various casting processes and casting defects helps effective radiographic evaluation. The major defects in castings and weldments are given below:

1. Gas porosity appears as round or elongated smooth dark spots, occurring individually or in clusters or distributed throughout the casting. This is caused by gas formation during solidification by

evaporation of moisture or volatile material from the mold surface. Insufficient core baking, venting or entrapment of air in the cope surface of the casting before complete solidification could also be the cause.

The term 'gas porosity' is used to refer to dark spots on the radiograph, whose diameters are usually 1.0 mm or less.

2. Gas holes appear as dark circular images, isolated or in clusters. These are caused by gas entrapment in molten metal. If the molten metal solidifies before all gases escape, the gas is entrapped in the casting, resulting in gas holes.
3. Micro-porosity/Shrinkage porosity/Micro-shrinkage: These appear as an overall mottled appearance in aluminum alloy castings, and dark streaks or a spongy appearance in magnesium alloys. These are very fine cavities, usually around the grain boundaries. This defect occurs in casting when overall metal shrinkage is more than the normally expected shrinkage factor. The defect is due to improper feeding of the molten metal and occurs when the pouring temperature is higher than the ideal temperature.
4. Shrinkage appears as dendrite, filamentary or jagged darkened areas. These are caused due to contraction of metal while the casting solidifies. This defect usually occurs when there is change in section thickness of the casting and non-uniformity of temperature at different thicknesses.
5. Cracks: These occur as hot tears or cold cracks (also called stress cracks). Hot tears appear as rugged dark lines of variable width and numerous branches with no definite line of continuity. Hot tears occur during or immediately after solidification. Cold cracks appear generally as a single straight, sharp dark line, usually continuous throughout the length. Such cracks occur when internal stresses are set up by a thermal gradient.
6. Dross appears as a dark, round or irregularly shaped images due to slag filling up the void entrapped in castings. These may look lighter if the density of inclusion is more than the density of the parent material. Inclusions may be due to slag, sand or oxides.
7. Cold shut appears as a dark line of variable length with a definite, smooth outline. Cold shuts are formed when two streams of molten metal flowing from different directions fail to unite. The formation of a cold shut is due to interrupted pouring, slow pouring or pouring the metal at too low a temperature.
8. Segregation appears as lighter or darker patches on the radiograph depending on the density of segregated constituents of the alloy. During the melting and casting processes, certain constituents of the alloy may separate from the alloy. This local concentration of the constituents results in a difference in densities on the radiograph, provided the density of the segregated portion is different from the density of the casting alloy.

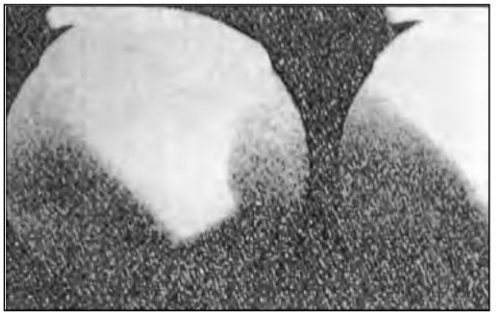
   It is possible to have local segregation, in which shrinkage or a hot tear are filled with segregate. The terms used for such indications are *shrinkage segregation* and *sealed hot-tear*, respectively.
9. Misruns appear as a prominent, darkened area of varying dimensions with a definite, smooth outline. Misruns are produced by failure of the molten metal to completely fill a section of casting, leaving the region void. This may occur due to lack of fluidity or pouring at too low a temperature.

10. Diffraction mottling appears as a spurious image on the radiograph and is not a casting defect. This appears as star-like image in case of austenitic steel and mottling in case of aluminum alloys. These are caused by the diffraction of radiation by the crystals of the metal. The mottling appearance vanishes if the radiograph is taken at a slightly changed angle of incidence.
11. Diffused chaplets are small bars with end plates used for maintaining the portion of mould core. These chaplets normally fuse with the casting. If not fused, these appear on the radiograph as darks, smooth lines conforming to the shape of the chaplet. This is caused by pouring the metal at too low a temperature to fuse the chaplet.

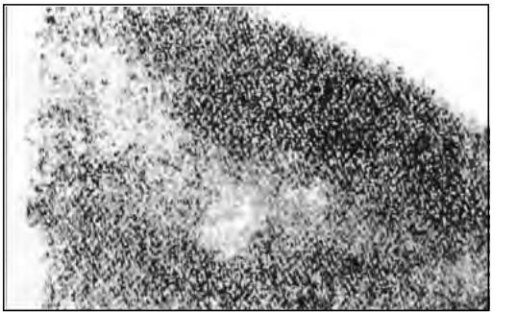
Defects in Welding

1. Porosity: See under casting defects in the previous section.
2. Slag inclusion and slag lines appear on the radiograph as dark, irregular shapes. These may be isolated, clustered or randomly distributed. A slag line appears as a linear dark shade, continuous or intermittent along the edge of the weld. Slag inclusions occur due to entrapment of foreign materials in the cavities during welding.
3. Incomplete penetration appears on the radiograph as continuous or intermittent dark lines, usually of uniform width, occurring in the middle of the weld. This is caused by the failure of the weld metal to fill the root gap.
4. Lack of fusion appears on the radiograph as a thick, dark line. It may also appear as diffused and wavy, depending upon the defect orientation with respect to the radiation beam. This defect is caused by the failure of the weld metal to fuse with the parent metal or previously deposited weld metal. In case of lack of sidewall fusion, the radiographic image shows the appearance of a straight, dark band parallel to the weld bead.
5. Cracks appear on the radiograph as sharp, straight or jagged dark lines with tapered ends. Cracks may appear in longitudinal or transverse directions. Cracks may occur in the weld and heat affected zones. The effect is caused by the rupture of the weld metal during solidification due to shrinkage or by fracture when cold, due to uneven stresses and poor handling.
6. Undercuts appear on the radiograph as dark lines of uneven width along the edge of the weld. This defect is caused by the formation of a groove or a channel on the surface of the base metal at the toe of the weld bead due to high temperature.
7. Burn through appears on the radiograph as a dark, round or elongated area surrounded by a lighter ring. This is caused by the melting of metal from the root of the weld or through the backing strip.
8. Icicles appear on the radiograph as isolated, white, rounded indications, occasionally with a small, dark spot in the center. This is caused by fused droplets of weld metal extending beyond the root of the weld.
9. Tungsten inclusions appear on the radiograph as white areas of round or irregular shape, either isolated or in clusters. This is caused by the entrapment of tungsten particles in the weld metal. These particles are broken pieces from the tungsten electrode.

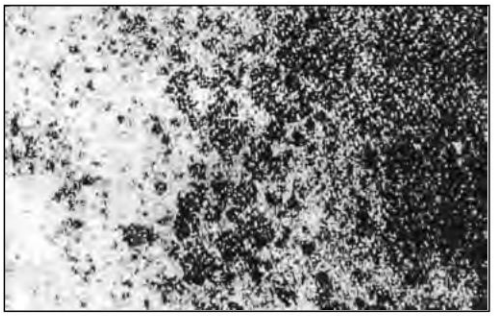
A few illustrative radiographs, showing some typical casting and welding defects, are given in Figs 2.24 to 2.26.



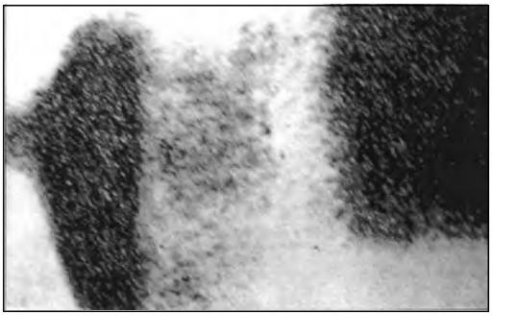
Gas Porosity (round and elongated) in Al-Cu alloy casting



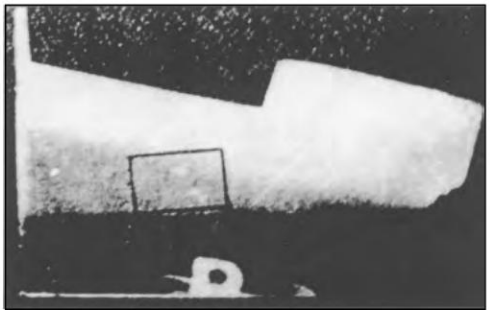
Gas porosity (round) coarse type in Al-Si alloy casting



Dross/cavities in Al-Si alloy casting



Micro-shrinkage in Al-Mg alloy casting



Dense inclusion in Al-Cu alloy casting

Filamentary shrinkage associated with shrink-porosity in Al-Cu alloy casting

Fig. 2.24 *Illustrative Radiographs for Defects*

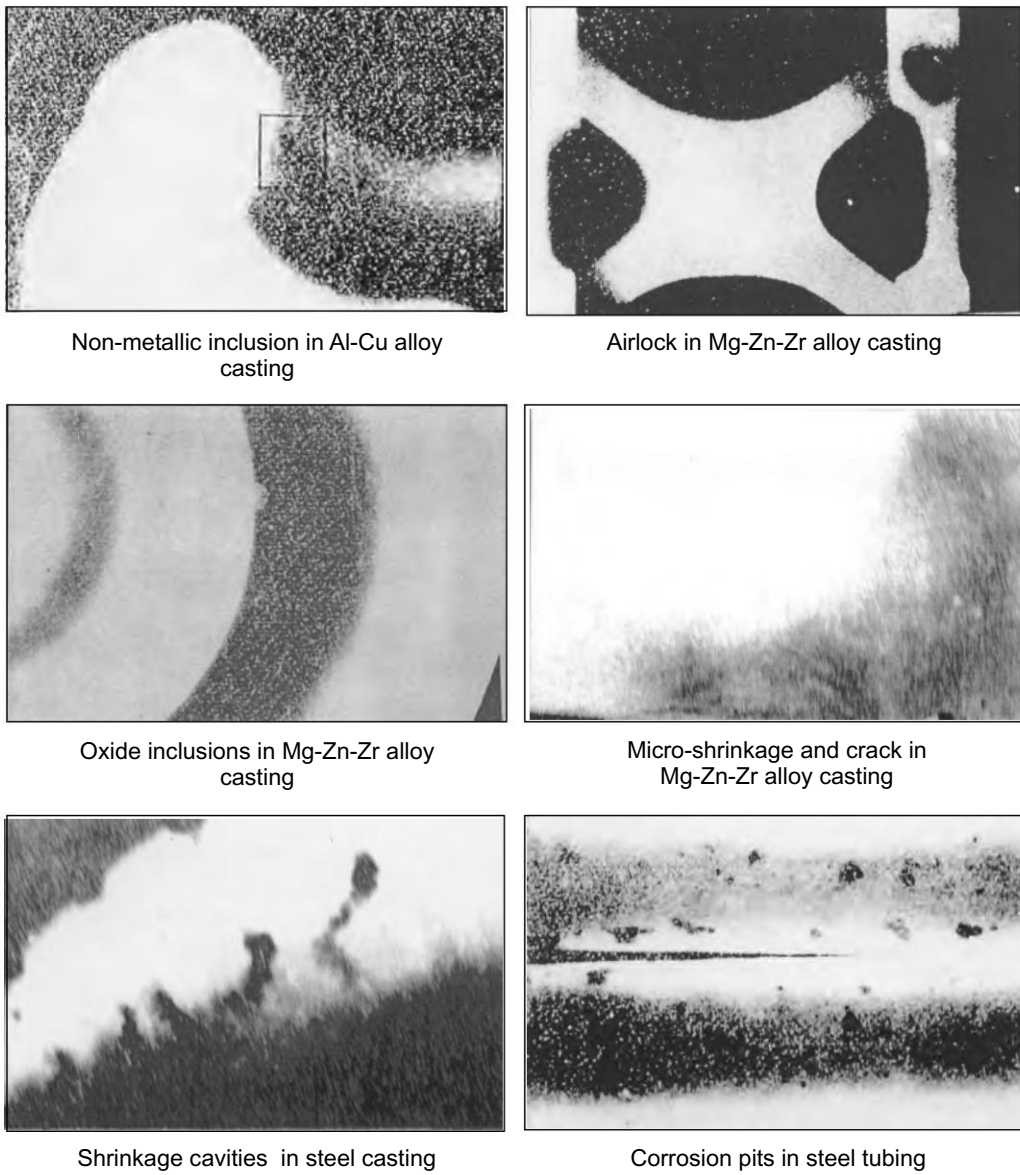


Fig. 2.25 *Illustrative Radiographs for Defects*

Unsatisfactory Radiographs—Causes and Correction

The factors contributing to satisfactory radiographs are:

- Correct exposure
- Proper handling of film during loading, unloading, processing and drying.

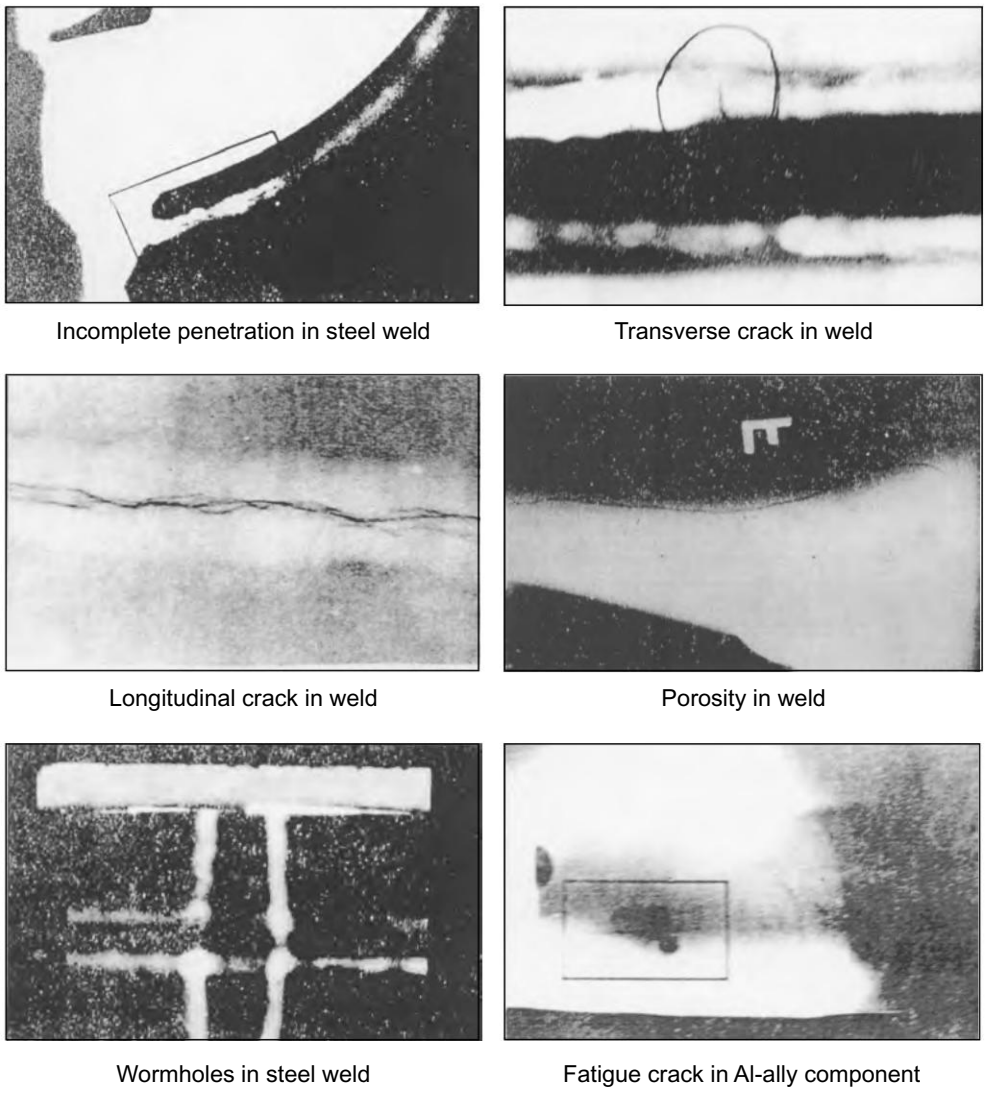


Fig. 2.26 *Illustrative Radiographs for Defects*

Deficiency in any of the above process results in an unsatisfactory radiograph.

Unsatisfactory radiographs may be due to improper storage of X-ray films and screens.

Faults in the handling, processing and storage of films results in unwanted appearances called artifacts on radiographs. Looking at the surface of a radiograph obliquely in reflected light identifies these. Table 2.12 shows the most common faults, reasons for their occurrence and remedial measures.

TABLE 2.12 *Unsatisfactory radiographs, causes and remedies*

Fault	*Cause*	*Remedy*
1. High density	Incorrect exposure	View radiograph under high intensity illuminator or decrease exposure. If density is readable but higher than acceptable, apply exposure correction with the help of H-D curve. Also check KV and mA meters and X-ray timer for proper functioning
	Over-development	Decrease development time; maintain temperature of developer solution and development time as per manufacturer's instruction. Follow time-temperature compensation guide. Also check dark room timer for proper functioning
2. Low density	Incorrect exposure	Increase exposure by applying exposure correction with the help of H-D curve
	Development time too short; temperature of developer solution very low or combination of both	Increase development time. Follow the temperature compensation guide. Check dark room timer
3. Fog	Exposure of film due to light leakage	Check film cassette for damage. Check light leak from outside by switching off dark room light
	Prolonged exposure to safety light	Check efficiency of safety lamp
	Safety-light lamp containing higher wattage bulb than specified	Use correct wattage lamp, compatible with the filter
	Bleached safe light	Replace filter
	Exposure to radiation leakage	Keep films away from radiation area
	Over-development	See (1)
	Incorrect preparation of developer solution	Discard developer and use new solution
	Prolonged inspection of film during development	Do not inspect film until it is developed
	Contaminated developer solution	Use clean containers while preparing the solution
	Deterioration of film resulting from storage in location where temperature and humidity are high	Maintain minimum film stock. Use old film first. Store film in cool and dry place
4. High contrast	Insufficient penetration, over-development, use of very high contrast films	Increase KV. Use film of lower contrast (fast film)
5. Low contrast	Excessive penetration, under-development, use of low contrast film	Reduce KV. Use film of high contrast

(*Contd*)

(*Table 2.12 Contd*)

Fault	***Cause***	***Remedy***
6. Streaks	Failure to agitate film during development, inspection of film during development, interaction of developer and fixer, film drying streaks	Agitate film occasionally, so that developer near the film surface is replaced by stronger solution. Do not inspect film under safety light during development. Ensure thorough washing of film. Use acid stop bath between developer and fixer. Use wetting agent before drying
7. Yellow stain on radiograph	Prolonged development in old, oxidized developer solution, omission of rinsing after development, use of exhausted fixer solution	Discard developer solution and replace with a fresh one. When not in use, keep the developer bath covered. Rinse film thoroughly in clean water before placing in fixer solution. Replace fixer solution
8. White scum on radiograph	Use of fixer solution that appears milky from a precipitation of aluminum sulphite due to incorrect mixing of fixing solution (Too warm when mixed or too rapidly or without stirring), carry over of developer on the film to fixer bath	Thoroughly rinse the film before putting it in fixer bath
9. Reticulation (net-like appearance on radiograph surface)	Extreme changes in temperature during processing	Maintain all processing solutions and water for rinsing and washing at the same temperature as far as possible. Use fixer solution having adequate hardening action
10. Frilling (loosening of emulsion from base)	Use of warm or exhausted fixer solution with no hardening action, high temperature of processing solution, prolonged washing at high temperature	Control temperature and replace fixer solution frequently. Increase rate of water flow through tank and wash for recommended time
11. Dark patches, nail marks and fingerprints	Drops of water or developer falling on to the film before development, electrical discharge marks due to low humidity and improper handling of film at various stages, marks from mechanical damage to the emulsion after exposure, drying marks due to high drying temperature or splashing of water drops on semi-dried film, handling film with greased or contaminated fingers before exposure or before development or fixing	Careful handling of film is required Use wetting agent before placing the film in drier. Use only two clean fingers while handling
12. Poor definition	Any or all of the following factors: object-film distance large, use of large focal spot, poor contact between film and screen, use of coarse grain film	Adjust exposure parameters carefully as explained earlier

Effectiveness and Limitations of Radiography

Each method of non-destructive testing is most effective in a particular domain of testing. Radiography has been used successfully in detecting three-dimensional defects and the assembly of components in areas normally inaccessible to other methods of testing. Table 2.13 gives the areas of effective applications of radiography. Here, it is important to note that location, assembly condition, working environment, the radiographer's skill and understanding, and the technique used contribute significantly to the effectiveness of radiography.

TABLE 2.13 *Effectiveness of radiography*

Nature of Product	*Effective Detection*	*Limits of Detection (Approximate linear size)*	
		Condition	*Limit of Detection (mm)*
Ingots, castings, weldments	Cavities, porosity, inclusions, shrinkage, hot tears, cold shuts, segregation, cracks (not very tight)	Laboratory	0.5
Assembly	Corrosion pits, cracks, entrapment of materials, misalignments	Production	2.0
		Service/field	5.0

2.4 Radiographic Technique and Acceptance Standard

In industries, one encounters a wide range of conditions in regard to component size, shape and composition. The objective of radiography is to examine and evaluate these components as clearly as possible. This requires standardizing the most efficient way of projecting the object, depending on its shape, size, thickness and composition. The major stages involved in establishing a standardized radiographic technique are:

1. Study of drawing, alloy composition, part geometry and inspection requirements
2. Conducting radiographic experiments to optimize exposure parameters
3. Selective destructive tests to validate radiographic observations
4. Documentation

Initially, necessary information such as areas of high stress, alloy composition, manufacturing process and inspection requirements must be collected and the geometry of the component, studied.

Radiographic experiments are conducted to optimize the following parameters:

- Energy of penetration (KV)
- Exposure factors (mA × time)
- Radiographic coverage, which implies projecting every portion of the component on the film. This may involve one or more normal and angular exposures of the component

- Exposure parameters need to be adjusted in such a way as to achieve IQI sensitivity better than 2%
- Selection of the type and size of film must match the requirements of the defect details and the component area coverage
- Density range of 1.5 to 3.0 over areas of interest
- Optimization of film focus distance, geometric un-sharpness, filters and screens and chemical processing of films

Selective destructive tests have to be conducted to establish the correlation of actual defects with their radiographic indication. This improves the confidence level of radiographers and proves the effectiveness of radiographic projection.

The mentioned experiments are repeated till a fair degree of agreement is achieved between the indication on the radiograph and the actual discontinuity in the component. Finally, optimized parameters for producing the most acceptable radiographs are documented for implementation. Thereafter, a periodic review and updating of technique is done in the light of feedback, information and experience gained.

The next step after establishing the technique is to assess the influence of various defects and discontinuities on the mechanical property of the components and fix a realistic limit of acceptance of the various discontinuities. Information about the limit of acceptance of various defect/discontinuities is usually available in the component design or the inspection document; in case such information is not available, defect-property correlation data is generated for fixing acceptance/rejection limit for various defects/discontinuities. The limit of acceptance of defects is decided based on the functional and stress classifications of the component in coordination with the designer.

Generally, components are classified into the following three categories:

- Class I: These components are often subjected to high temperature, pressure, fatigue and impact stresses. The failure of such components can cause significant danger to operating personnel or would result in serious operational penalties or loss of the entire system. One should be extremely careful in the examination and assessment of such components
- Class II: These are stressed components whose failure may not have as drastic an effect as in case of Class I components. Failure of these components may lead to the damage of subassemblies that can be replaced without causing serious damage to the system. One should be extremely careful in the examination and assessment of such components
- Class III: These are low stressed or unstressed components, whose failure does not cause any significant damage to the system. Often, radiographic examination is not required for such components

Further consideration is given to component area classification according to the distribution of stresses. This enables the fixing of a realistic limit of acceptance of a defect in different areas of the component.

- Material composition/specification, which provides information about inherent susceptibility of the material to some defects
- Machining allowance: This information helps salvage and rework assessment

General guidelines for acceptance limits for radiographically observed defects for castings and weldments are given in the following table. Guidelines are given in terms of plate numbers of ASTM reference radiograph E155.

TABLE 2.14 *Guideline of acceptance limits of defects in aluminum alloy castings*

Permissible Defects	*ASTM E155 Reference Radiograph Plate Numbers*	*High Stressed Area*	*Low Stressed Area*	*Balance*
Gas holes	1.1	2	3	5
Gas porosity (round)	1.21	2	3	5
Gas porosity (elongated)	1.22	1	2	4
Shrinkage sponge	2.2	1	2	4
Shrinkage cavity	2.1	None	1	2
Foreign material (less dense)	3.11	2	3	4
Foreign material (denser)	3.12	1	2	3

TABLE 2.15 *Guideline of acceptance limits of defects in magnesium alloy castings*

Permissible Defects	*ASTM E155 Reference Radiograph Plate Numbers*	*High Stressed Area*	*Low Stressed Area*	*Balance*
Gas holes	1.1	2	3	5
Micro shrinkage (feathery)	2.31	2	3	4
Micro shrinkage (sponge)	2.32	2	3	4
Foreign Material (less dense)	3.11	2	3	4
Foreign material (more dense)	3.12	1	1	2
Micro-shrinkage (Mg-Al alloys)	2.31	1	2	3
Reacted sand inclusion	Vol. II	1	1	2
Eutectic segregation	Vol. II	1	2	3
Gravity segregation	Vol. II	1	2	3

TABLE 2.16 *Guidelines of acceptance limits of defects in steel investment castings*

Permissible Defects	*ASTM E155 Reference Radiograph Plate Numbers*	*High Stressed Area*	*Low Stressed Area*	*Balance*
Gas holes	Plate 1/8" Plate 3/8" Plate 3/4"	3 4 4	5 5 5	6 6 6
Foreign material (less dense)	Plate 1/8" Plate 3/8" Plate 3/4"	3 4 4	5 5	6 6 6

(*Contd*)

(*Table 2.16 Contd*)

Permissible Defects	*ASTM E155 Reference Radiograph Plate Numbers*	*High Stressed Area*	*Low Stressed Area*	*Balance*
Shrinkage (sponge)	Plate 1/8" Plate 3/8" Plate 3/4"	2 1 1	6 3 2	4 3 3
Shrinkage cavity	Plate 1/8" Plate 3/8" Plate 3/4"	0 0 1	0 0 2	0 0 3
Shrinkage (dendritic)	Plate 1/8" Plate 3/8" Plate 3/4"	2 2 2	2 3 3	4 3 3

Note: Plate 1/8" is applicable to material thickness (6.4 mm) and under
Plate 3/8" is applicable to material thickness (6.4 mm to 12.7 mm)
Plate 3/4" is applicable to material thickness (12.7 mm to 25.4 mm)

TABLE 2.17 *Guidelines of acceptance limits of defects in steel fusion welds*

Permissible Defects	*Permissible Limits*
Isolated pore or individual pores in a group	1. Diameter 1.5 mm for thickness (t) up to 25 mm 2. Diameter 3.0 mm for $t > 25$ mm and < 50 mm 3. Diameter 4.5 mm for $t > 50$ mm and < 75 mm
Uniformly distributed porosity or localized porosity	1% area (as seen in the radiograph) for thickness up to 25 mm
Linear porosity	Parallel to the axis of the weld is not permitted
Worm holes (isolated)	Length not greater than 6 mm and width not greater than 1.5 mm (as seen in the radiograph)
Slag inclusions	Distance between two inclusions should be greater than 5 times the length of the larger one
(i) Individual and parallel to the weld axis (as seen on radiograph)	For 18 mm thickness Length less than or equal to $t/2$ and not greater than 6 mm and width not greater than 1.5 mm (ii) For thickness 18 mm –75 mm Length not greater than $t/3$ Width not greater than 1.5 mm
(ii) Linear groups	Aggregate length should not exceed 8% of length of group, which should not exceed $12t$ in length
(iii) Randomly oriented (not parallel to the weld axis)	Length not greater than $t/3$, subject to a maximum of 6 mm and width not greater than 1.5 mm

Note: A linear group is defined as the number of inclusions, in line and parallel to the weld axis, where separation between adjacent inclusions is not more than 6 times the length of the longest inclusion within the group.

TABLE 2.18 *Guideline for acceptance limit of defects for light alloy fusion welds*

Isolated defects	(i) Length Width	≤ 2 mm ≤ 0.5 mm	For weld thickness in the path of X-ray beam ≤ 2 mm
	(ii) Length Width	≤ *t* mm ≤ *t*/4 mm	For weld thickness in the path of beam = *t* mm
	(iii) Cumulative length of defects	≤ 10 mm	For total length of weldments > 200 mm
	(iv) Cumulative length of defects	≤ K/20 mm	For total length of weldments K < 200 mm

Note: A chain of small defects is considered a single and continuous defect if the separation between them is less than 1/3 of the length of the smallest adjacent defect.

2.5 Special Radiographic Techniques

2.5.1 Neutron Radiography

We have seen that the attenuation of X-rays and gamma rays increases with increasing atomic number of the test object. Therefore, it is difficult to radiograph objects of low atomic number in an assembly of high atomic number materials. However, the attenuation of thermal neutrons in many low atomic number materials is high compared to their attenuation in high atomic number materials. Figure 2.27 gives an idea of the attenuation co-efficient for X-rays and thermal neutrons. High attenuation of many low atomic number materials enables the use of thermal neutrons as a complementary tool of radiography to investigate objects of low atomic number entrapped in materials of high atomic number.

Neutrons are produced by the fission of high atomic number elements (e.g. Uranium) in reactors. These are also obtained from radioactive isotopes and accelerators. Table 2.19 gives the intensity range and radiographic applications of neutrons obtained from various sources.

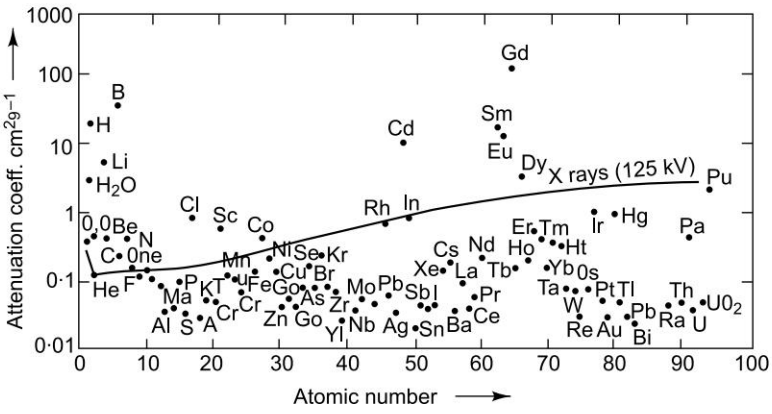


Fig. 2.27 *Mass Attenuation Coefficient of the Elements for X-rays and Thermal Neutrons*

TABLE 2.19 *Thermal neutron intensity and radiographic applications*

Source	*Intensity (n/cm²/sec)*	*Applicability and Limitation*
Radio isotope	$10-10^4$ (Low intensity)	• Poor radiographic resolution • Long exposure time • Portable source
Accelerator	10^3–10^6 (Medium intensity)	• Medium radiographic resolution • Medium exposure time • Source may be portable
Reactor	10^5–10^8 (High intensity)	• Good radiographic resolution • Short exposure time • Fixed installation

For radiographic applications, high-energy neutrons from various sources are slowed down by surrounding them with light materials like water, paraffin, carbon, etc. (called moderators). By collision with these materials, neutrons lose their energy and attain a thermal equilibrium with the approximate energy range of 0.1 to 0.3 eV. These neutrons are called 'thermal neutrons' and are used for radiography.

Techniques of Thermal Neutron Radiography

Basically, the test object is placed in a thermal neutron beam in front of an image detector. The neutron beam is obtained from any of the neutron sources indicated in Table 2.19. Fast neutrons are slowed to lower energy by surrounding them with a moderator. The neutrons are then collimated for improved sharpness of the radiographic image. Figure 2.28 shows an arrangement for thermal neutron radiography.

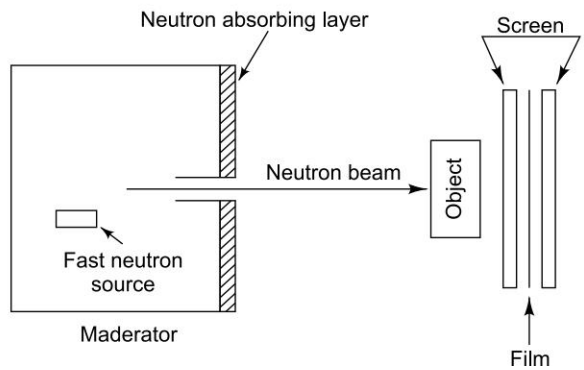


Fig. 2.28 *Arrangement for Thermal Neutron Radiography*

Recording Neutron Image

Neutrons do not affect photographic film. Therefore, special methods are employed to record the radiographic image. Two methods are generally used:

- Direct exposure method
- Transfer exposure method.

In the direct exposure method, after emerging from the test object, thermal neutrons are allowed to fall on a cassette in which X-ray film is sandwiched between thin foils of metals called converters, which are made of materials such as Gadolinium. Under the action of neutron bombardment, the

Gadolinium foil is converted into a gamma ray emitter. Gamma rays emitted from the Gadolinium foil affects the film.

In the transfer exposure method, neutrons, after emerging from the object, are allowed to fall on screens made of Indium or Dysprosium. As a result of neutron irradiation, these materials are made radioactive with half-lives of 54 minutes and 2.35 hours respectively. After irradiation with neutrons, this image-carrying screen is brought in contact with X-ray film loaded in cassettes to record the image. Figure 2.29 illustrates the arrangement.

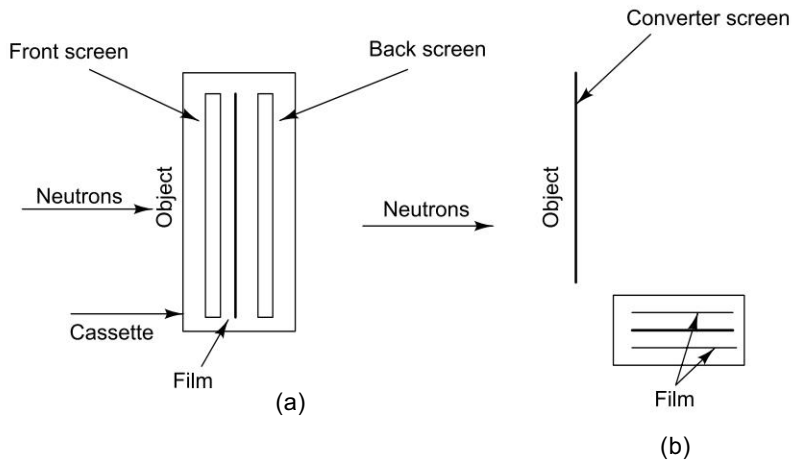


Fig. 2.29 *(a) Direct Exposure (b) Transfer Exposure*

Micro-radiography

This technique is used to study minute discontinuities in or the segregation of constituents in alloys and also to study cemented joints in corrugated cardboards and biological materials such as tissue sections, insects, seeds, etc.

A very thin specimen ($\simeq$ 0.5 mm) with a smooth surface is prepared and kept in close contact with an ultra fine grain film. The film holder is usually a low atomic number material to keep X-ray absorption minimum. A continuous X-ray spectrum as well as characteristic *k*-radiation is used in the energy range 5–50 KV. Continuous radiation is used for studying the segregation of alloy constituents having large variations in atomic number, whereas characteristic radiation is used to study the segregation of constituents having small variations in atomic number. The micro-radiographs are studied through a microscope after enlarging them by optical projection.

Flash Radiography

This is used to study objects in motion, such as projectiles in flight, moving machinery, fuel injection, high velocity impact, shockwave in solids, welding and casting processes, etc. In conventional radiography, one uses relatively low energy and long exposure, whereas in flash radiography, one makes use of high energy X-rays with a high dose output and very short exposure (~ micro seconds). In this system, a condenser charged to pre-determine voltage is discharged through an X-ray tube by field emission. The

tube current, during discharge of the condenser, is of the order of several thousand amperes. A single flash is enough to produce a good radiograph. Flash radiographic units have been made in the range of 50 – 2000 KV. Salt screens are used for low KV flash radiography, whereas lead screens can be used at high KV to improve the quality of radiographs. Further, sharp images are obtained by synchronizing the velocity of moving objects with the triggering of X-ray flashes.

Autoradiography

In this radiographic process, the source of radiation is embedded in the test object. The recording film is kept in contact with the object, which, after due exposure and development, gives an Autoradiograph. This process is used for the detection and distribution of radioactive materials in the object. There are two types of autoradiographic processes: macro autoradiography and micro autoradiography.

Macro autoradiography is used to study the progress of homogenization at different heat treatments of some metals having radioactive elements intentionally added during the melting stage. Micro autoradiography is used to study the frictional wear and tear of engineering components, the uptake of bone-seeking radio-isotopes and the study of biological specimens. Micro autoradiography requires ultra-fine grain, very high contrast film, and is studied under high magnification.

Electron Radiography

In this process, the radiographic image of thin materials is recorded using photoelectrons instead of X-rays. Heavily filtered X-rays are made to fall on a metal foil of high atomic number (e.g. lead). The photoelectrons ejected from the lead foil pass through the specimen and expose the photographic emulsion in amounts depending on the energy and number of electrons that have penetrated the specimen. An important requirement to obtain a good electron radiograph is that lead foil; the specimen and the fine grain film should be in intimate contact during exposure.

The energy of X-rays used is of the order of 250 – 300 KV and the filter thickness, 5 mm of copper plus 5 mm of aluminum. This technique is used to study paper watermarks, paper structure, ink overprints, leaves and fabrics.

Another method to produce electron radiographs is by electron emission. This technique records the image of the surface components of the materials that are not distinguishable by visible light. In this case, the ultra-fine grain film emulsion is placed in intimate contact with the polished surface of the specimen and heavily filtered, hard X-rays are allowed to impinge on the polished surface of the specimen through the emulsion. Electrons are emitted from the surface of the specimen in amounts depending on the atomic number of the components on the specimen surface. The film emulsion is exposed accordingly. This technique is used to study the material structure, to authenticate rare postage stamps, fingerprints etc.

High Definition Radiography

High definition radiography is basically a method to detect and geometrically enlarge very small defects (~ 0.01 mm). The radiographic unit used for this purpose has extremely fine focus (~ 0.001 mm). Such ultra-fine X-ray units are used to detect and study microporosity in turbine blades or to examine fine cooling holes in cast turbine blades and other precision components used in areas of high technology.

High definition X-ray units usually operate in the 25–120 KV range with mA ranging from 0.5 to 2. Fine grain, high contrast films are invariably used for recording the image. Enlargement of the image is achieved by maintaining a suitable distance between the object and the film. Figure 2.30 illustrates this.

Proton Radiography

Mono-energetic protons from particle accelerators are used for purposes of medial as well as industrial radiography of the sections.

Proton radiography makes use of the fact that even a small thickness change at a depth of 80–90% of its 'range' results in a large change in the flux of protons emerging out of the test piece, compared to X-rays. Figure 2.31 shows this. This creates a significant density change on the film. A proton beam from an accelerator is diverted and magnetically focused on the test object. The emergent beam is recorded on fine grain X-ray film or on photographic film (black and white or colored). It is possible to detect thickness changes as small as 0.05% and 0.01% by proton radiography. High-energy protons from particle accelerators can be used to radiograph objects of higher section thicknesses.

Proton radiography has the potential of application both in medical and industrial fields.

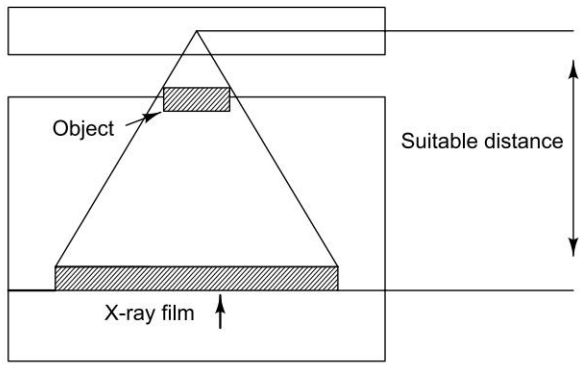


Fig. 2.30 *High Definition Exposure Arrangement*

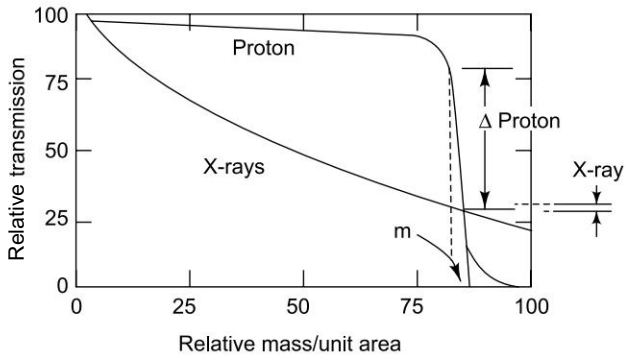


Fig. 2.31 *Relative Transmission of X-rays and Protons*

X-ray-computed Tomography (CT)

X-ray-computed tomography has been applied in recent years to evaluate small metallic and composite components. In this system, a fan shaped X-ray beam is passed through the test object to get a radiographic image of two-dimensional slices of the object, without interference from overlying or underlying areas. Figure 2.32 illustrates this. The method is highly sensitive to small differences (<1%) in material density.

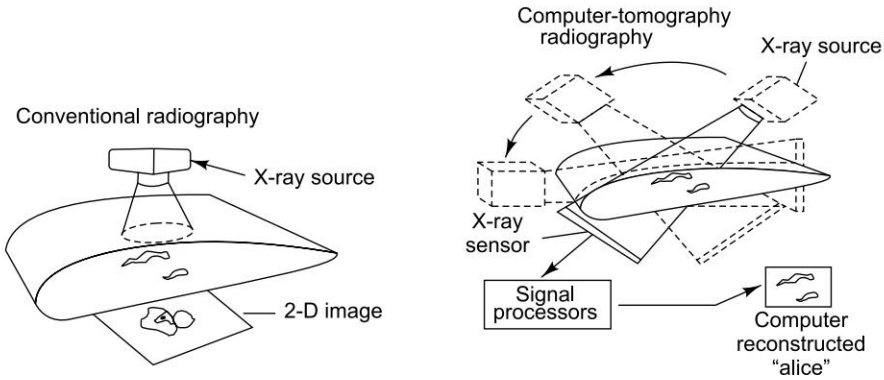


Fig. 2.32 *X-ray-Computed Tomography*

2.6 Safety Aspects of Industrial Radiography

In industrial radiography, high-energy X-ray and gamma radiation is used. Since radiation can damage the body, it is essential that persons working with radiation be aware of harmful effects and take necessary steps for protection. Careless handling of radiation would give rise to exposure to the human body, resulting in undesirable somatic and genetic effects. These effects could be noticed only after a lapse of time, except in the case of excessive exposure. In view of this, the Government of India has promulgated "Radiation Protection Rules 1971" under the atomic energy Act, 1962 (33 of 1962). The rules are aimed at ensuring safe working conditions for all radiation workers and provide for a prescription of an operation dose limit. Under these rules it is necessary that:

1. All radiation workers be monitored regularly
2. The dose received by the person be well within prescribed limits
3. Causes of excessive exposure be detected with minimum delay and suitable corrective measures taken to avoid future excessive exposure
4. The cumulative records of the individual radiation workers be maintained for the entire period during which they work with the radiation source

Radiation protection is the prevention of illness or injury from over-exposure to X-rays and nuclear radiation. Radiation is considered hazardous when a person is exposed to it beyond a certain limit. The human body is exposed to background radiation from naturally occurring radio-isotopes and from cosmic rays. Based on experience and studies on the effects of radiation, a maximum permissible level has been specified for occupational personnel and the general public. Radiation protection activity consists of:

(i) Measurement and evaluation of exposure level
(ii) Introducing measures to minimize exposure and eliminate needless exposure

Radiation hazards are of two types:

(i) External radiation hazards from exposure to X-ray, gamma ray or radioactive contamination. Radiation hazard is different for different types of radiations. The higher the penetratability of radiation, the greater is the damage to tissues. X-rays and gamma rays are more penetrating, beta is less and alpha particles are least penetrating
(ii) Internal radiation exposure results when radioactive material or contamination gets inside the body by way of breathing, swallowing or through cuts in the skin. The amount of material absorbed, the time for which material remains in body and the type of isotope, all contribute to the damage of body cells

The effect of alpha particles is enormous when it is inside the body. Beta particles can cause both internal and external hazards.

2.6.1 Radiation Dose

The total radiation dose received by a person during the period of employment in the radiation area is called 'occupational dose'. The basic requirement as per the controlling agencies in various countries is that the radiation worker should not receive an occupational dose in excess of the following:

TABLE 2.20 *Permissible radiation dose*

Individual Radiation Worker	(i) Cumulative dose for five-year block : 100 mSV (ii) Annual effective dose in any calendar year during five-year block not to exceed 30 mSv (iii) Cumulative effective dose exceeding 20 mSv to be investigated
Pregnant women directly engaged in radiation work	Dose limit 2 mSv to the surface of women's abdomen
General Public	$1/10^{th}$ of the limit prescribed for radiation worker

[Note: 1 mSv = 0.1 rem]

2.6.2 Radiation Effect

There are two types of biological effects caused by overdose of radiation, somatic effects and genetic effects. Somatic effects are the physical effect on the body of the individual who receives radiation. Damage to blood cells, skin cells, tissue cells, etc. are considered somatic effects. Genetic effects are those that can be passed on to the next generation or to later descendents as hereditary characteristics. The exact nature of the effects of radiation on the future generation is still unknown, although cases of genetic effects have been observed on some animals.

The effects of overdose of radiation exposure are not necessarily detectable immediately after exposure. They are noticed after some delay. To avoid the ill effects of radiation exposure, it is necessary to keep the dosage within prescribed limits or less, by observing good safety practices.

2.6.3 Radiation Measuring Devices

Some typical devices used for the measurement of radiation are: Ionization Chamber, Geiger Counter, Proportional Counter, Scintillation Counter and Photographic Film.

Devices used for monitoring radiation areas are portable units to measure radiation levels at different locations in the vicinity of radiation sources. This is useful for immediate assessment of adequacy or otherwise for radiation protection. Radiation survey meters, which are Ionization Chamber type or Geiger-Muller type, are used to measure doses in terms of milli-Roentgen (mr) per hour at any distance from radiation sources. Readings ranging from 0.01 to 0.02 mr/hr are quite common for background radiation. Two devices are used for monitoring radiation exposure of personnel working in a radiation area. These are pocket dosimeter, which gives an instant indication of accumulated dose of X or Gamma radiation and films, which are encased in a metal holder. The film holder is worn on the outer clothing or on the chest. It records the radiation dose falling on it. It is used to detect gamma rays, X-rays, high-energy beta radiation and thermal neutrons. The metal holder contains an open window to allow beta radiation to reach the film, a plastic fitter to evaluate gamma radiation, two copper filters—one to evaluate X-ray exposure below 250 KV and the other to evaluate exposure above 250 KV—and a 0.5 mm-thick cadmium filter to evaluate thermal neutrons.

After the film has been worn for a period of a fortnight or a month, it is removed and developed. The density of the film is measured by a densitometer.

The dose received is determined by correlating the measured density with a set of pre-established calibrated curves on a graph showing density versus dose. Figure 2.33 shows a film badge.

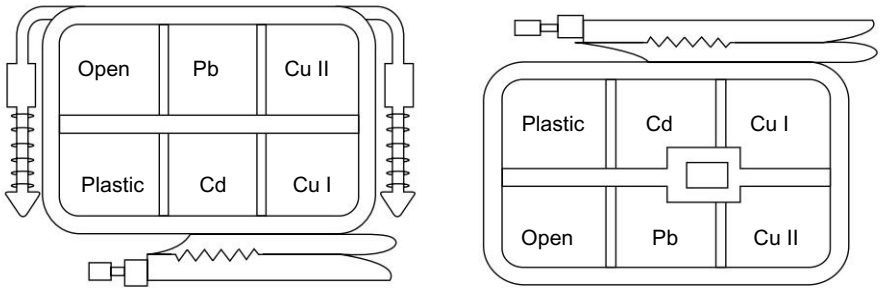


Fig. 2.33 *Film Badge*

The advantage of a film badge is that it provides a permanent record of an individual's cumulative exposure.

2.6.4 Radiation Protection

Three basic means are used as a protective measures to keep radiation exposure within allowable limits: time, distance and shielding. Exposure received by a person is directly proportional to the length of time he stays in the radiation area. The radiation exposure dose rate at any distance from the radiation source is calculated using the standard dose rate of each isotope and radiation output of X-ray units. The standard dose rate for an isotope is usually expressed in terms of RHM value, the radiation level in Roentgen/hr at 1 meter from 1 Curie of a gamma ray emitting isotope. These values are fixed for each isotope. Table 2.21 gives the RHM values of some important gamma ray isotopes.

For X-ray sources, the radiation output depends on the KV, the tube current, the focal spot size, the type of rectification and the amount of filtration. Usually, suppliers of X-ray units provide radiation output data for each X-ray unit. It is expressed as 'Roentgen per minute at one meter from the X-ray source.

TABLE 2.21 *RHM value of isotopes*

Isotope	*RHM Value (r/hr/ci at 1 meter)*
Co-60	1.3
Ir-192	0.5
Cs-137	0.32
Cs-137	0.87
Ra-226	0.825

The radiation intensity varies inversely as the square of the distance from the source. Therefore, the greater the distance from the source, the lower the radiation exposure. The concept of the inverse square law for radiation protection is valid only for radiation in open space. For closed enclosures, scattered radiation limits the validity of the inverse square law for calculating protection for closed enclosures.

Shielding is a means of providing personnel safety by placing absorbing material between the radiation source and the personnel in the area. The efficiency of shielding depends upon the nature of the absorbing material and its thickness. Generally, high atomic number materials are used for shielding.

Materials such as lead, tungsten, steel and depleted uranium are used as shielding material for housing radioactive isotopes. Concrete, granite, brick and concrete with barium sulfate are some of the materials used as structural shielding for protection against X and gamma rays. Tables 2.22 and 2.23 give the shielding thicknesses of different types of materials.

TABLE 2.22 *Protective barrier required for 75 to 300 KV X-rays with tube current of 10 mA*

Target Distance (m)	*Lead Thickness (mm)*					
	75 KV	100 KV	150 KV	200 KV	250 KV	300 KV
0.6	2.2	3.4	4.3	6.7	11.8	16.0
0.9	2.0	3.1	4.0	6.2	10.9	14.7
1.5	1.7	2.7	3.6	5.5	9.6	13.1
2.4	1.5	2.4	3.2	4.8	8.5	11.8
3.0	1.3	2.2	3.0	4.5	8.1	11.1
4.6	1.1	1.9	2.6	4.0	7.1	9.9
6.1	1.0	1.7	2.4	3.6	6.4	9.0
15.2	0.5	1.1	1.7	2.4	4.3	6.2

TABLE 2.23 *Typical X-ray and gamma exposure room shielding for maximum protection*

Source KV	*Approx. HVL**		*Typical Primary Shield Thickness for Maximum Protection*	
	Lead (mm)	*Concrete (mm)*	*Lead (mm)*	*Concrete (mm)*
50	0.05	5.0	1	100
70	0.18	13.0	1	150
100	0.24	18.0	4	200
150	0.30	23.0	6	300
200	0.50	25.0	8	350
250	0.80	28.0	12	400
300	1.30	30.0	21	500
400	2.20	33.0	40	600
10 Ci – Ir^{192}	6.0	42.0	70	600
10 Ci – Co^{60}	12.0	65.0	–	1100

* HVL (Half Value Layer) shielding stops half the radiation of a given intensity.

2.6.5 Safety Aspects of Gamma Ray Cameras

Gamma radiation sources emit radiation continuously. Therefore, every precaution needs to be taken to ensure its safe storage so that leakage radiation does not exceed the maximum permissible level. As the energy and source strength increase the thickness of the container material also increases. It is necessary to ensure the following:

(i) At a distance of 5 cm from the surface of the camera, the maximum radiation level should not exceed 100 mr/hr; the average radiation level should not exceed 20 mr/hr

(ii) At a distance of 1 meter from the source, the maximum radiation level should not exceed 10 mr/hr; the average radiation level should not exceed 1 mr/hr

(iii) Locking devices should be provided for cameras so that the camera can be switched 'on' and 'off' only by authorized persons. The camera should be identified conspicuously with the nature and strength of radiation sources together with the radiation warning signal

(iv) The gamma camera, when not in use, should be stored in a safe place in an isolated room or in a pit inside the exposure room with a radiation warning symbol at the entrance of the storage area. The maximum radiation leakage around such an area should not exceed 0.25 mr/hr

(v) During transportation, radiation sources must be sealed in accordance with the relevant radiation regulation of the country

2.6.6 Protection Measures Against X-rays

Indoor Radiography

The walls of the exposure room should be of adequate thickness so that the radiation intensity outside the exposure room is well within the permissible limits. The doors of the exposure room should be lined with adequate thickness of lead sheets with proper overlapping. Interlock on the exposure room doors, an alarm and warning lights should be connected through the control panel. The mechanism should be so arranged that if the exposure room door is opened inadvertently during exposure, the equipment is automatically switched off and cannot be switched on while the door is open. The control panel should be located in a separate room adjacent to the exposure room. The cable connecting the tube head and the control panel should pass through a small duct at the floor level, at an angle to the wall thickness. Such ducts should be lined and both the openings should be covered with lead sheets.

Outdoor Radiography

The outdoor area around the X-ray unit is cordoned off and the area is radiation surveyed. No-one is allowed to enter the unsafe area. Warning signals are kept around the cordoned-off area.

In addition to protection for radiographers, it is necessary to take steps to protect other personnel who may have access to the radiographic site. Field radiography hardly ever eliminates exposure doses. Therefore, exposure should be planned and monitored. Survey meters and personnel dosimeters should be used as monitoring devices.

Personnel Record

Persons should undergo a medical examination before being employed as radiation workers. During employment, each person should undergo annual medical examination. Reports of the medical examination

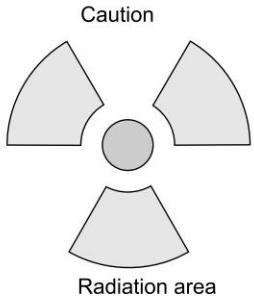


Fig. 2.34 *Radiation Warning Symbol (This sign is posted where radio-active materials are handled or where radiation producing equipment is used. This sign is used as a warning to protect people from being exposed to radiation.)*

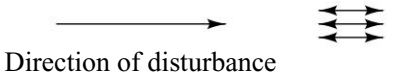
and cumulative dose reports of each worker should be maintained for future reference. Radiation warning symbol should be displayed, whereever radiation producing equipment is used. The symbol is shown in Fig. 2.34.

3 ULTRASONICS

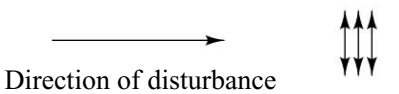
3.1 PRINCIPLE OF WAVE PROPAGATION

Sound energy above the audible frequency of 16,000 Hz is designated as ultrasonics. It is a form of mechanical energy and propagates through the material medium as a stress wave by direct and intimate mass contacts. The propagation of these waves through the material medium is sustained and controlled by the elastic properties of the medium. Also, in-homogeneities and discontinuities in the medium significantly modify and modulate the propagation of these waves. Thus, ultrasonics is a study of a form of mechanical energy, its propagation and its interaction with the medium through which it propagates. It is a common experience that whenever a medium is disturbed by a force, the particles of the medium are set into oscillation. The oscillation of the particles is either longitudinal or transverse or a combination of both. In any of these types of oscillations, there is no bodily movement of the mass of the medium as a whole; only the disturbance propagates. On the basis of particle displacement of the medium, ultrasonic waves are classified as:

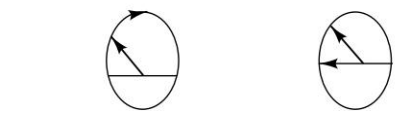
- Longitudinal waves particle



- Transverse waves particle



- Compressional and flexural waves (Rayleigh waves and Lamb waves)



Rayleigh waves (also called surface waves): During propagation of these waves, particle oscillation follows elliptical orbits as shown in Fig. 3.1.

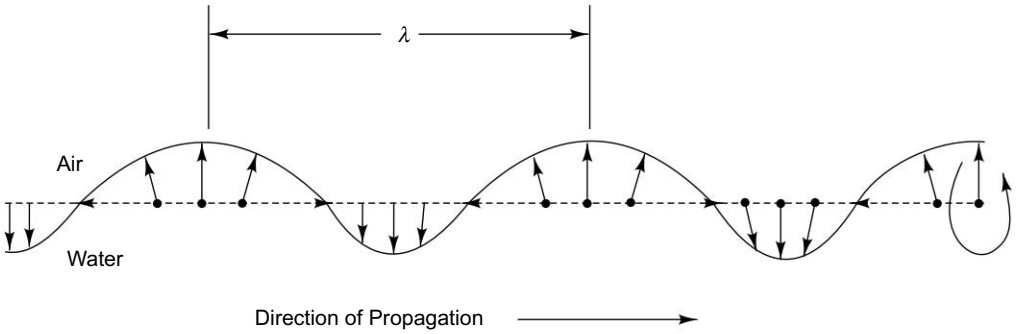


Fig. 3.1 *Rayleigh Waves (Surface Waves)*

The major axis of the ellipse is perpendicular to the surface along which the wave moves; the minor axis is parallel to the direction of wave motion. These waves travel along flat or curved surfaces of thick solids. The depth of these waves below the surface, with effective intensity, is of the order of a wavelength only. These waves are used to detect flaws or cracks on or near the surface of test objects.

Lamb waves (also called flexural waves or plate waves): These waves are produced in thin metals whose thickness is comparable to the wavelength. These waves are complex in nature; elastic properties, structure, dimensions of the medium and cyclic frequency determine their propagation through a medium. These waves travel both symmetrically and asymmetrically with respect to the neutral axis of the material medium. The velocity of these waves is influenced by the angle at which they enter the material. Figures 3.2 (a) and (b) illustrate these waves. Symmetrical lamb waves have compressional particle displacement along the neutral axis and elliptical particle displacement along the surface.

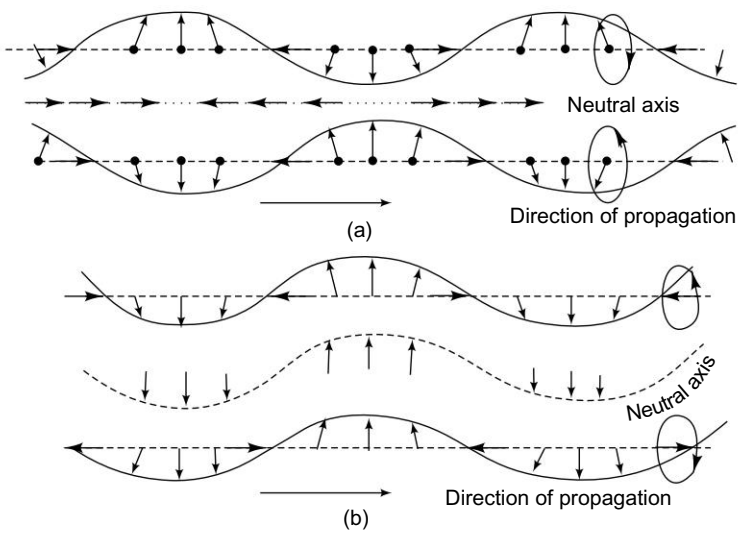


Fig. 3.2 *(a) Symmetric Lamb Waves (b) Asymmetric Lamb Waves*

3.1.1 Wave Propagation

When waves succeed one after the other at regular intervals, the particles, whether moving in the longitudinal or in the transverse direction, execute a periodic motion. If an infinite medium is subjected to a periodic force, the particle of the medium near the point of application of force is displaced from its position of rest. Its displacement at any time after the start of the disturbance depends on its position relative to the direction of propagation of the disturbance. As a result of the impulse transmitted by neighboring particles situated near the origin of the applied force, a disturbance is induced in the mass and energy transfer takes place from one particle to the next. This second particle influences the third in a similar manner, and so on. In this way, the energy passes from element to element till it is attenuated. The periodic force that produces this disturbance (or wave) in the medium could be longitudinal, transverse or elliptical. The rate of propagation of the wave generated (and hence the rate of propagation of energy associated with the wave) depends on the type of vibration associated with it and the properties of the medium such as elastic modulii, density and the frequency of the wave. It has been mentioned that ultrasonic waves travel as stress waves. In a gaseous medium these travel only as a longitudinal wave; in most liquids they travel as longitudinal and surface waves, and in solids, they travel as longitudinal, transverse, surface or lamb waves.

In so far as ultrasonic testing is concerned, we will confine our attention to the propagation of waves in solids.

The velocity of propagation of various types of waves is as follows:

$$C_L = \left\{\left(\frac{E}{\rho}\right)\left(\frac{1-\sigma}{(1+\sigma)(1-\sigma)}\right)\right\}^{1/2}$$

$$C_T = \left\{\left(\frac{E}{\rho}\right)\left(\frac{1}{2(1+\sigma)}\right)\right\}^{1/2}$$

$$C_S = \frac{(0.87+1.12\sigma)}{1+\sigma}\left\{\frac{E}{\rho}\frac{1}{2(1+\sigma)}\right\}^{1/2}$$

where C_L = longitudinal velocity — E = youngs modulus

C_T = transverse velocity — ρ = volume density of the medium

C_S = surface wave velocity — σ = Poission ratio

3.1.2 Pressure and Intensity of Sound Waves

Sound energy travels as waves of compression and rarefaction. This causes pressure variation in the medium as the waves travel through it. The variation of pressure is periodical. For all practical calculations, the root mean square (rms) of the pressure is used and given by:

$$P_{\text{rms}} = \frac{P_0}{\sqrt{2}} \quad \text{where } P_0 \text{ is the maximum pressure}$$

The intensity of sound at a point some distance from the source is given by:

$$I = \frac{W}{A}$$

where W = rate of energy propagation and A = area perpendicular to the direction of propagation. This intensity depends on the

- distance of the area from the source
- properties of the medium
- orientation of the area with respect to the direction of energy propagation

In practice, it is difficult to measure the intensity, but easier to measure the pressure. Pressure is related to intensity and energy by the following relation:

$$I = \frac{P_{\text{rms}}^2}{\rho C} \quad \text{where } \rho = \text{density of the medium}$$

$$E = \frac{P_{\text{rms}}^2}{\rho C^2} \qquad C = \text{velocity of sound in the medium}$$

Sound pressure, power and intensity are measured on a logarithm scale. The scale is designated as the decibel scale and is a comparative scale. The level of two powers w_1 and w_2 is expressed on the decibel scale as

$$10 \log_{10} \left(\frac{w_1}{w_2} \right)$$

This is the decibel level of w_1 above w_2 and is written as 'dB'.

The decibel scale is applied to sound measurements by the following definitions:

(i) Sound pressure level $= 10 \log_{10} \left(\frac{w}{w_0} \right)$ with reference to w_0

(ii) Sound intensity level $= 10 \log_{10} \left(\frac{I}{I_0} \right)$ with reference to I_0

(iii) Sound pressure level $= 10 \log_{10} \left(\frac{P^2}{P_0^2} \right)$ with reference to P_0

$$= 20 \log_{10} \left(\frac{P}{P_0} \right)$$

The usual reference levels used in the study of sound are:

$w_0 = 10^{-12}$ watts

$I_0 = 10^{-12}$ watts/m^2

$P_0 = 0.00002$ newtons/meter^2

$= 0.0002$ Dynes/cm^2 $= 20$ μp (micropascals)

In an ultrasonic test system, signal amplitudes are measured as electrical voltages only and the acoustic power is proportional to the square of voltage; therefore, the level of acoustic power is given by:

$10 \log_{10} \left(\frac{V_1^2}{V_2^2} \right)$ with reference to $V_2 = 20 \log_{10} \left(\frac{V_1}{V_1} \right)$

Note: Sometimes the Neperian logarithm base e is used instead of the common logarithm base '10'. The two are related as: 1 Neper = 0.115 dB or 1 dB = 8.69 Neper.

3.1.3 Acoustic Impedance

This implies the resistance of a medium to the passage of sonic energy through it. In acoustics, the specific impedance is defined as the ratio of pressure to particle velocity.

Thus, specific impedance $Z = p/v$

For plane harmonic waves $p/v = \rho c$

ρ = density of the medium

v = particle velocity

c = velocity of sound in the medium

$\therefore$ $Z = \rho c$, Z is expressed in kg/m^2 sec or in rayls

where ρ is expressed in kg/m^3 and c is expressed in m/sec

Z depends on the structure and metallurgical condition of the material, as these factors affect both ρ and c.

3.2 Reflection, Refraction, Diffraction, Mode Conversion and Attenuation

3.2.1 Reflection

The Snail's law of reflection, as applicable to light rays, is applicable to acoustics, provided that the dimensions of the reflecting medium are large compared with the wavelength. The law may be stated as:

(a) The incident ray, the reflected ray and the normal, at the point of incidence, lie in one plane.

(b) The angle of incidence is equal to the angle of reflection as shown in Fig. 3.3.

MN = Reflecting surface

AO = Incident beam

OC = Reflected beam

OB = Normal at the point of incidence

$\angle AOB = i$ = Angle of incidence

$\angle BOC = r$ = Angle of reflection

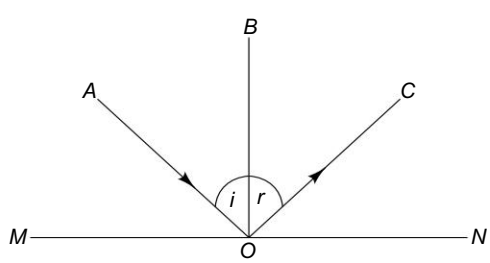


Fig. 3.3 *Reflection*

3.2.2 Refraction

Sound waves incident obliquely on the boundary separating two media, where the velocities of propagation are different, undergo an abrupt change in direction. This phenomenon is known as refraction. The laws governing the phenomenon of sound refraction are similar to those applicable to light waves. The laws may be stated as:

(a) The incident ray, the normal to the refracting surface at the point of incidence and the refracted ray lie in one plane.

(b) The sine of the angle of incidence bears a constant ratio to the sine of the angle of refraction, which is equivalent to the ratio of the sound velocities in the media concerned. Figure 3.4 illustrates this.

MN = Refraction surface
AO = Incident beam
OC = Refracted beam
$\sin i/\sin r$ = constant = C_1/C_2
BOB' = Normal at the point of incidence
$\angle AOB$ = Angle of incidence i
$\angle B'OC$ = Angle of refraction r

where C_1 = Velocity of sound in medium I
C_2 = Velocity of sound in medium II

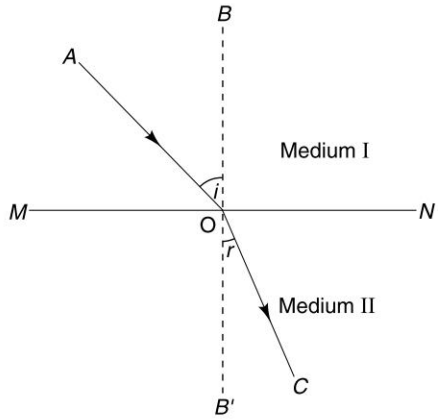


Fig. 3.4 *Refraction*

When sound waves are incident on an interface of two media, they are reflected, transmitted and scattered. Figure 3.5 illustrates the situation for normal incidence. Characteristic parameters associated with waves, namely particle velocity (v), amplitude (A) and pressure (P) undergo a change after reflection and transmission. Assuming that the incident wave is plane and there is no loss of energy in any medium, we have for reasons of continuity:

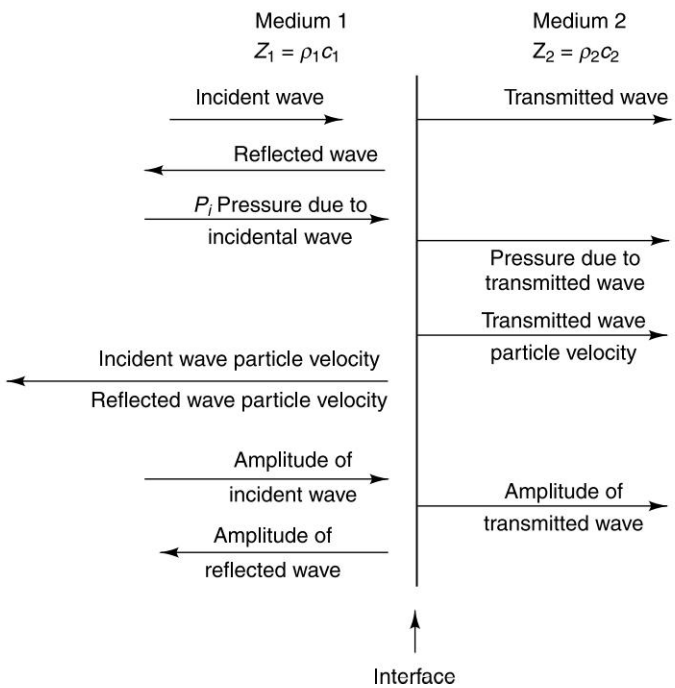


Fig. 3.5 *Sonic Behavior at an Interface*

On either side of the interface, the pressures and particle velocities normal to the boundary are same. This leads to following relationship:

$$\left.\begin{aligned} P_i + P_r &= P_t \\ V_i + V_r &= V_t \\ A_i + A_r &= A_t \end{aligned}\right\} \quad \text{at the boundary}$$

and

$$\frac{A_i}{\rho_1 c_1} + \frac{A_r}{\rho_1 c_1} = \frac{A_i}{\rho_2 c_2} \tag{1}$$

From (1) we get

Reflection coefficient $$R = \frac{A_r}{A_i} = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Similarly, transmission coefficient $$T = \frac{A_t}{A_i} = \frac{2\rho_2 c_2}{\rho_2 c_2 + \rho_1 c_1} = \frac{2Z_2}{Z_2 + Z_1}$$

R and T may be used to calculate the percentage of the incident sound pressure in reflected and transmitted waves.

3.2.3 Mode Conversion

When a sound wave strikes an interface at an angle between two materials having different acoustic impedances, some of its energy is converted into modes of vibration other than the incident mode. If we consider a force F acting on the interface at an angle as shown in Fig. 3.6, the force may be resolved into mutually perpendicular directions, $F \sin \alpha$ along the boundary and $F \cos \alpha$ at right angles to it. Under the action of these two components, the medium is subjected to both compressional and shear forces.

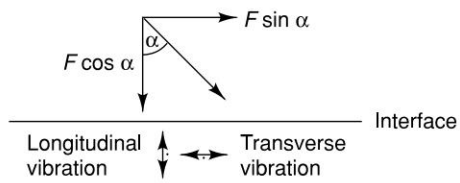


Fig. 3.6 *Mode Conversion at Oblique Incidence*

This situation gives rise to longitudinal as well as transverse modes of vibration.

At normal incidence, F will have no component along the boundary; hence, a shear mode of vibration is not produced. Thus, for any angle of incidence other than normal, every longitudinal wave has a reflected and refracted component. Both reflected and refracted components contain longitudinal and transverse waves.

i = Angle of incidence
r_1 = Angle of reflection for longitudinal wave
r_2 = Angle of reflection for transverse wave
r_3 = Angle of refraction for transverse wave
r_4 = Angle of refraction for longitudinal wave

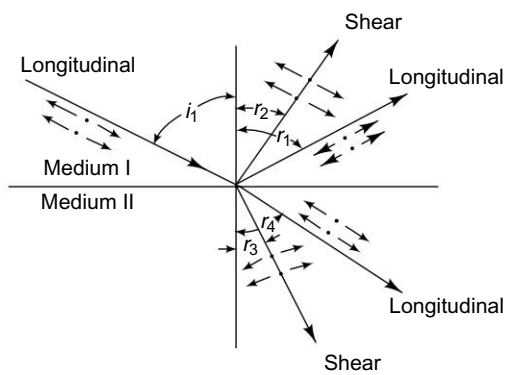


Fig. 3.7 *Mode Conversion at Oblique Incidence*

As the angle of incidence increases, the angle of refraction for a longitudinal wave reaches 90°. The angle of incidence corresponding to a 90° angle of refraction is called first critical angle. For further increase in the angle of incidence, the longitudinal wave is totally reflected in medium I and no longitudinal wave exists in medium II; only the refracted shear wave exists. If the angle of incidence is increased further, the angle of incidence for which the angle of refraction for transverse waves is 90° is called the second critical angle for a transverse wave (or shear wave). Further increase in the angle of incidence results in total reflection for both longitudinal and transverse wave modes.

The similar situation holds good for transverse waves incident at the interface. Thus, both transverse and longitudinal waves are generated at the interface at oblique incidence, provided that the angle of incidence is less than the critical value. It is also found that besides longitudinal and transverse waves, surface and lamb waves are also generated. The transformation and distribution of incident sound energy into various modes of vibration at the interface, for oblique incidence, is called mode conversion.

3.2.4 Diffraction

Whenever sound waves encounter an obstacle, their direction of propagation changes. This change of direction or departure from the original direction of propagation is called diffraction. Diffraction takes place when the wavelength of sound is comparable to the dimensions of the obstacle. If the dimension of the obstacle is large compared to the wavelength, reflection takes place. Diffraction affects non-destructive testing adversely as it prevents the full utilization of sound energy. The sound energy is lost in destructive interference as a result of diffraction; also, energy in the sound field is changed as it spreads out from its origin.

3.2.5 Attenuation

As the ultrasonic beam impinges on a surface and propagates through the medium, the energy of the beam gets divided into reflected, refracted, mode converted, diffracted and scattered beams. Part of this energy gets absorbed. The loss of ultrasonic energy due to scattering and absorption is referred to as attenuation.

Scattering includes losses due to such factors as reflection, refraction and diffraction. While absorption includes loss due to conversion of sound energy into kinetic energy of particles of the medium, attenuation increases with the increasing frequency of the ultrasonic wave.

The scattering losses are strongly influenced by the in-homogeneities of the material such as porosity, inclusions, coarse grains, cracks and agglomeration of elastically different materials. Even in sound materials, the presence of preferred orientation in metallic materials or a strongly directed lay up in composites, contribute to in-homogeneity in the path of the ultrasonic beam. The relationship between the wavelength and extent of in-homogeneity also affects the scattering and attenuation losses.

The effect of absorption is to reduce the energy in a predictable manner, as the sound energy transverses a given thickness of a material either in incident or reflected mode. From the viewpoint of practical testing, this loss can be compensated by increasing the input energy in terms of voltage and magnification.

However, attenuation resulting from scattering is unpredictable and cannot be compensated by increasing or decreasing the input energy. Scattering limits the detectability of small size defects.

The total attenuation is represented by:

$$P = P_0 e^{-\alpha t}$$

where P_0 is the initial sound pressure

P is the final pressure after the wave has traversed a thickness t

α is the linear coefficient of attenuation

or $$-\alpha t = \log \frac{P}{P_0}$$

or $$\alpha t = \log \frac{P_0}{P} \text{ Bels}$$

or $$\alpha t = 10 \log \frac{P_0}{P} \text{ decibels}$$

In terms of initial and final electrical voltages, which are used in measuring sonic amplitude, the above relation can be written as

$$\alpha t = 10 \log \frac{V_0^2}{V^2}$$

$$= 20 \log \frac{V_0}{V}$$

where V_0 = initial voltage

V = final voltage after the wave has traversed a thickness t

The size of the grains and the variation of homogeneity has a significant effect on scattering. This aspect will be discussed in a later section.

3.3 Sound Field

The space around a source of sound over which its effect is felt is called sound field. The effect is assessed by the parameters that characterize sound. The characteristic parameters associated with sound at any point in its field are the variation of density of the material through which it travels, the velocity or displacement of the particle of the medium or the pressure variation that accompanies the propagation of sound.

For the ultrasonic test of materials, the assessment of pressure variation in the field is of significance. Ultrasonic waves are generated utilizing the piezo-electric effect in certain materials. These piezo-electric materials are usually in the form of plates, which can be considered as an assembly of point sources of spherical waves. These waves travel in the test material with different amplitudes and phases and give rise to diffraction maxima and minima immediately in front of the piezo-electric plate. This zone is called 'Nearzone' or 'Fresnel zone'. After the near zone the waves travel as a divergent beam. This zone is called 'Far zone' or 'Fraunhoffer zone'. Figure 3.8 illustrates the situation.

For a circular piezo-electric plate, the sound field has axial pressure maxima located at points given by:

$$X = \frac{D^2 - \lambda^2 (2m+1)^2}{4\lambda (2m+1)}$$

where D = Diameter of the piezo-electric element
λ = Wavelength
m = 0, 1, 2, 3, …

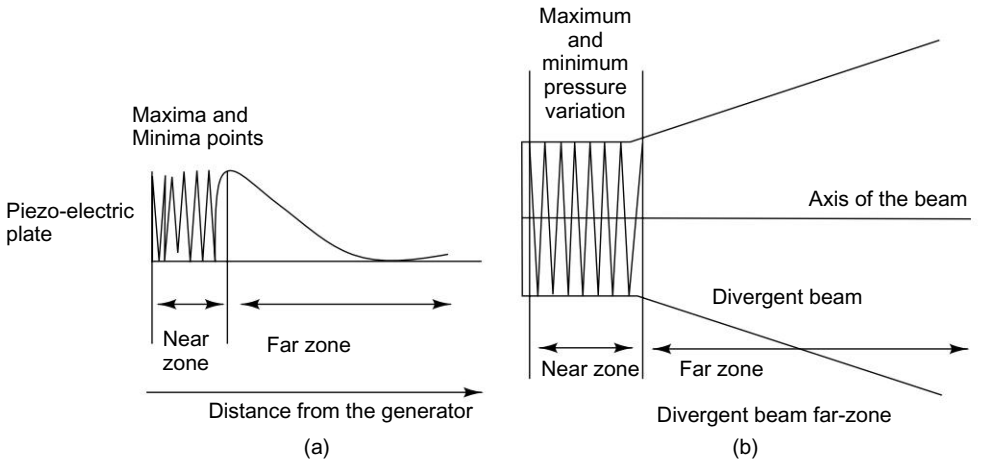


Fig. 3.8 *Pressure Variation in the Forward Direction from the Surface of a Piezo-Electric Plate*

The length of the near field is determined by locating the peak of the final maximum pressure. This is determined by making $m = 0$ in the relationship. Hence, we have length of the near zone = $\frac{D^2 - \lambda^2}{4\lambda}$.

For $D \gg \lambda$, length of the near zone = $D^2/4\lambda$

The number of maxima and minima is given by:

$M = D/\lambda$

In the far zone or Fraunhoffer zone, the sound waves travel as a diverging beam. This zone is interference free. In this zone, the intensity of sound decreases as the square of the distance from the piezo-electric plate. From the viewpoint of ultrasonic testing, the far field is of interest to us. The sound beam diverges in the far field, as the distance increases as shown in Fig. 3.9.

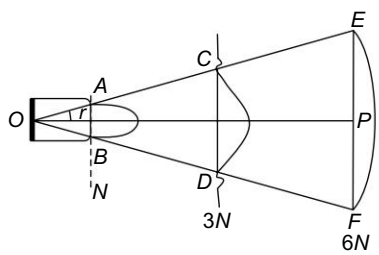


Fig. 3.9 *Divergence and Pressure Variation in the Far Field*

It may be seen that the pressure amplitude is maximum along the axis OP, but with increasing distance, it keeps decreasing. Also, the pressure amplitude reduces when observed away from the axis. The zero pressures for distances N, $3N$ and $6N$ are at A, B, C, D, E and F. The divergence profile of the beam is obtained by joining the zero pressure points, viz. O, A, C, E and O, B, D, F, etc. The angle that this line makes with the axis of the beam is called the angle of divergence. The angle of divergence is defined as:

$$\sin \gamma = \frac{C\lambda}{D}$$

$$\sin \gamma = \frac{C \cdot V}{fD}$$

f = frequency
D = diameter of generator
γ = angle of divergence
V = velocity of sound

C is a constant that assumes the following values at various pressure points across the beam cross-section. The pressure at any point along the axis OP is taken as 100% pressure point.

C = 0.44 for 70% pressure point
= 0.56 for 50% pressure point
= 1.08 for 10% pressure point
= 1.20 for 0% pressure point

The 70% pressure point corresponds to 30% reduction in pressure and is referred to as the 3 dB drop point. Similarly, the 50% and 10% pressure points are referred to as the 6 dB and the 20 dB drop points respectively.

The values of C mentioned are valid for small values of λ/D (small values of divergence) and circular generators. If the generator is not circular, the relation is not accurate. In such cases, divergence is assessed experimentally.

The ultrasonic field variation can be controlled by suitably adjusting the diameter and frequency of the ultrasonic generator. Using a large diameter transducer and high frequency can reduce divergence to a small value, which is desirable for ultrasonic testing. However, large diameter generators also increase the near zone (also called zone of confusion). Therefore, in practice, divergence is kept within a tolerable range by a compromise between diameter and frequency of the generator.

3.4 Piezo-Electric Effect

The word 'piezo' means pressure and piezo-electric effect implies pressure electricity. Certain naturally occurring crystals like quartz and tourmaline show piezo-electric property. The crystals, when subjected to mechanical vibration, produce electrical pulses in a perpendicular direction. Also, when these crystals are subjected to high frequency electrical pulses, dimensional distortion is observed in a perpendicular direction. Continuous impingement of electrical pulses results in mechanical vibration of the crystal. This shows that the piezo-electric effect is a reversible phenomenon. If a sound wave, with its alternating expansion and compression, impinges on the piezo-electric plate, the latter produces an alternating voltage with the frequency of the wave. The generated voltage is proportional to the amplitude of sound pressure. Thus, a direct piezo-electric effect is used to receive ultrasound, while the reciprocal effect is used for generating ultrasound.

Some piezo-electric materials like quartz, tourmaline and rochell salt occur in nature. But most of the commercially used piezo-electric materials are synthetic compounds such as ammonium dihydrogen phosphate, lithium sulfate, lead niobate, potassium dihydrogen phosphate and polycrystalline ceramics (e.g., barium titanate, lead zirconate titanate, etc.).

Synthetic crystals are grown from solutions under controlled conditions. Polycrystalline ceramics are produced by calcining and sintering at high temperature to achieve piezo-electric property. These ceramics are cooled under the influence of high intensity polarizing D.C. potential (~ 5 KV). The crystal domains align with the field and remain in that condition even after the field is removed. The temperature at which polarization is achieved is called 'Curie temperature' and if the crystal is heated above this

temperature, the crystal loses its piezo-electric property. Natural crystals also have their own Curie temperature. The following table shows some of the properties of popularly used piezo-electric crystals.

TABLE 3.1 *Some common properties of piezo-electric materials*

Property	*Quartz (SiO^2)*	*Lithium Sulfate ($LiSO^4$)*	*Barium Titanate ($BaTiO^3$)*	*Lead Zirconate Titanate PZT*
Density (gm/cm^3)	2.63	2.06	5.4	7.5
Acoustic velocity (m/sec)	5740	5460	5100	4000
Curie temperature (°C)	576	130	120	190 –350
Acoustic impedance ($N.s/m^3.10^6$)	15.2	11.2	27	30

3.5 Ultrasonic Transducers and Their Characteristics

Ultrasonic transducers (or probes or search units) are devices to generate and receive ultrasound. For non-destructive test purposes, piezo-electric elements of suitable dimensions are used to generate the complete range of ultrasonic frequencies at all levels of intensities. The transducers convert electrical energy into mechanical energy (vibration) and vice-versa, as explained earlier.

A transducer essentially consists of a case, a piezo-electric element, backing material, electrodes, connectors and protection for the piezo-electric element from mechanical damage. Figure 3.10 shows the essential elements of a transducer assembly.

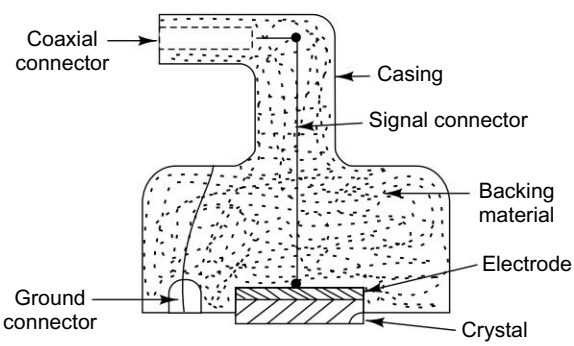


Fig. 3.10 *Elements of a Transducer Assembly*

A casing is the housing within which various elements are contained. It is metallic or molded plastic. When the piezo-electric element is subjected to electrical impulses, it vibrates or 'rings' for a long time. For non-destructive testing, a long period of vibration is undesirable as it adversely affects defect resolution capability. To prevent excessive ringing, highly attenuating materials (called backing materials) are bonded to the back face of the piezo-electric element. Backing materials consist of a mixture of graphite, powdered metals (e.g. tungsten) and a metal oxide of random grain size. Wear resistance of the crystal can be increased without sacrificing resolution and sensitivity by the use of a thin layer of aluminum oxide or boron carbide.

3.5.1 Types of Transducers

Normal Beam Transducers

These transducers are used for contact testing and immersion testing. Transducers generate, transmit and receive longitudinal waves, normal to the test surface. Figure 3.11 shows a normal beam contact transducer and Fig. 3.12 shows an immersion transducer. In the immersion type of testing, the piezo-electric element is made completely waterproof and a grounding electrode is provided in the front face.

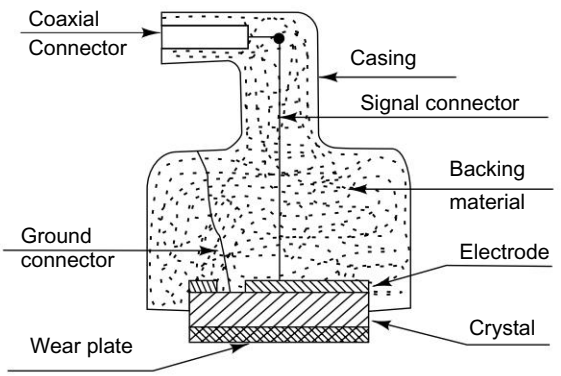


Fig. 3.11 *Normal Beam with Wear Plate*

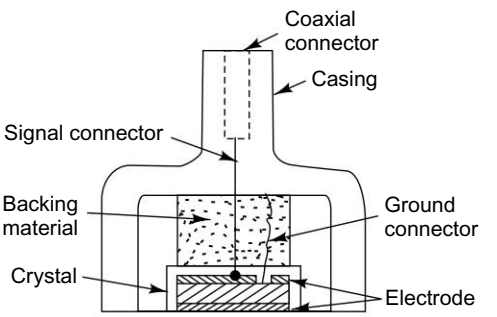


Fig. 3.12 *Immersion Search Unit*

Angle Beam Transducers

These are contact type transducers that transmit and receive longitudinal waves at an angle to the test material surface. During the transmission of the wave, the longitudinal wave is mode converted to a shear or surface wave on entering the material.

During reception, the shear or surface wave is mode converted back to the longitudinal wave. Figure 3.13 shows the essential elements of an angle beam transducer.

The transducer is similar to a normal beam probe, except that a wedge cut at an appropriate angle is attached to the normal beam transducer.

Apart from those mentioned, various types of transducers, in different sizes and frequencies, have been developed for specific inspection applications. Some of these are discussed next.

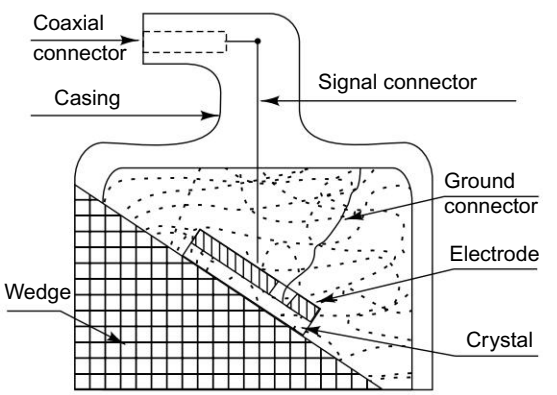


Fig. 3.13 *Angle Beam Contact Search Unit*

Dual Element Transducers

In this type, the transmitter and receiver elements are separated with a cork-divider. Figure 3.14 illustrates this.

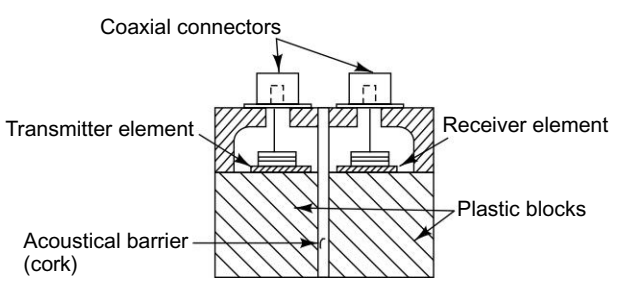


Fig. 3.14 *Dual Element Transducer*

Focused Transducers

Focused transducers are designed to concentrate acoustic energy into a small area. This improves intensity, sensitivity and resolution and also reduces the effect of acoustic noise. An acoustic lens of predetermined focal length is attached to a normal beam probe. Sometimes it is incorporated in the transducer facing. The focusing could be cylindrical or spherical. While examining

curved surfaces, cylindrical focusing is used. Spherical focusing concentrates the sound beam into a cone. Spherical focusing is preferred while examining near surface defects. Figure 3.15 illustrates focused transducers.

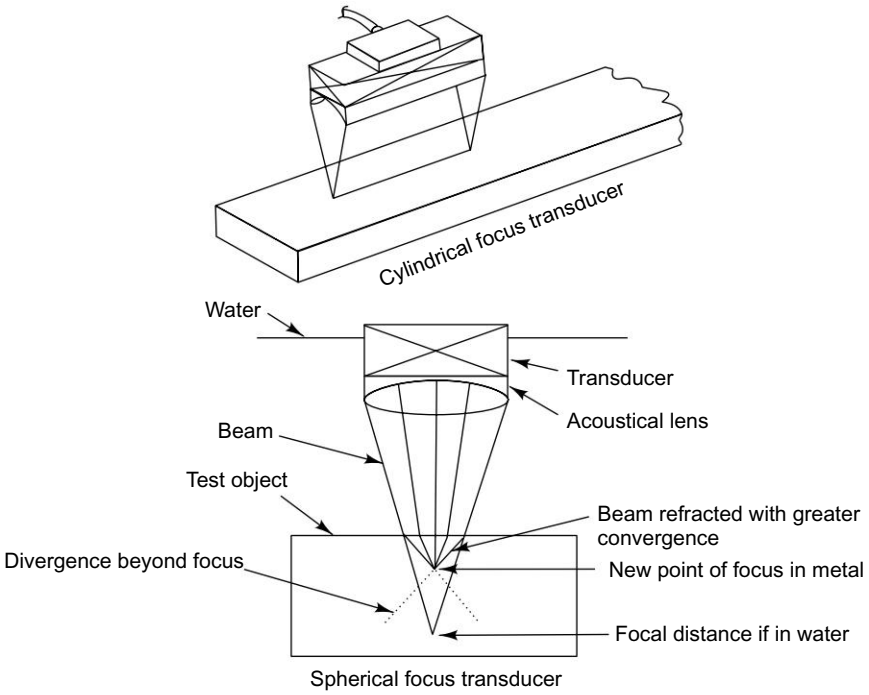


Fig. 3.15 *Cylindrical and Spherical Focus Transducers*

The velocity of sound in the solid medium is greater than that in air or liquid; therefore, a sonic beam incident upon a liquid-solid interface is refracted away from the normal. Hence, a concave lens will converge and a convex lens will diverge the sonic beam. The focal length of a plano-concave lens, which is mostly used in a sonic focusing system, is given by

$$f = \frac{R}{1 - cl/cs}$$

R = Radius of curvature of concave surface

cl = velocity in liquid

cs = velocity in lens material

Solid lenses are made of polystyrene and liquid lenses are made of carbon-tetrachloride contained in a thin-walled container.

Special Transducers

Various types of transducers, in different sizes and frequencies, have been developed for non-standard test conditions. Some of these are:

- Dual crystal in a common holder, with a cork divider between transmitter and receiver
- Large piezo-electric plate size (25 mm × 100 mm or above) and small piezo-electric elements (3 mm or less)

- Mosaics with three or more piezo-electric elements
- High frequency type (25 MHz or more)
- Sandwich and tandem arrangement type
- *Y*-cut crystals for shear wave generation

3.5.2 Characteristics of Transducers

A transducer is characterized by its:

- Electro-mechanical coefficient, which is the ratio of electrical energy appearing as mechanical energy to the applied electrical energy. To achieve maximum conversion of energy, the crystal is operated at its resonance frequency (the thickness of crystal is made a multiple of half wave length)
- Sensitivity, which refers to the relationship between the amplitude of electrical voltage impinging on the crystal and the magnitude of the ultrasonic signal produced. Therefore, it determines the smallest defect size that can be detected
- Resolution, which refers to the ability to separate signals from two discontinuities located at only slightly different depths. A long pulse has poor resolving power. Short pulses are desirable for high resolutions
- Quality factor

The mechanical quality factor is defined by the ratio:

$$Q = \frac{f_0}{f_2 - f_1} = \frac{f_0}{\Delta f}$$

where f_0 = Central resonant frequency

f_2 = frequency above f_0 where sonic amplitude is 70% of that at f_0

f_1 = frequency below f_0 where sonic amplitude is 70% of that at f_0

Δf = Transducer band

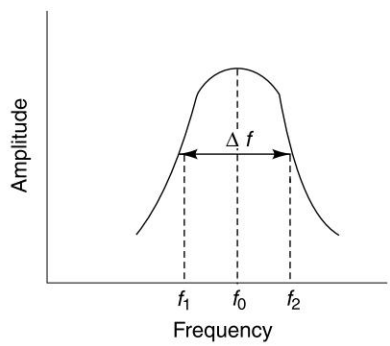


Fig. 3.16

A wide-band transducer has sharp and well-defined pressure changes within the near zone. The resolution of a broadband width transducer decreases with distance in materials. The rate of decrease depends on the attenuation characteristic of the material, which in turn depends on grain size, grain boundary condition and the relationship between grain size and wavelength. Higher frequencies are attenuated faster. This tends to reduce bandwidth and lower the centered frequency, thus causing loss of resolution.

3.6 Ultrasonic Equipment and Variables Affecting Ultrasonic Test

The essential features of an ultrasonic pulse-echo flaw detector are shown in Fig. 3.17.

The pulse-echo flaw detector contains the following important sections:

1. Pulse generator
2. Transmitter receiver unit
3. Synchronizer

4. Sweep generator
5. Receiver amplifier
6. CRT display
7. Transducer

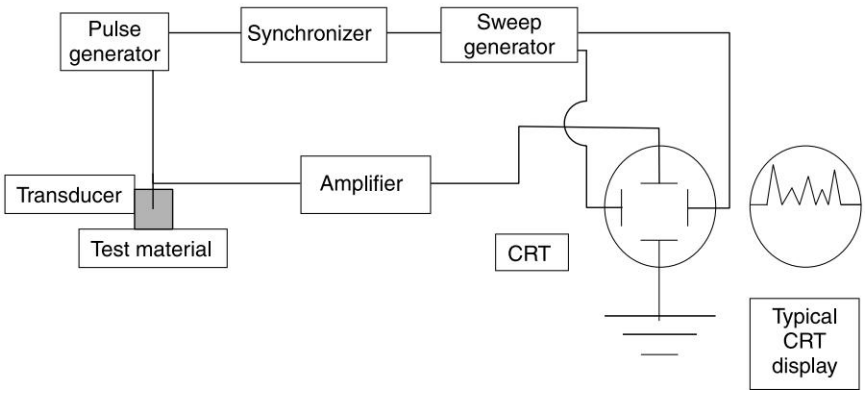


Fig. 3.17 *Block Diagram of a Pulse-Echo System*

1. Pulse generator: This component of the pulse-echo system acts in two ways—it energizes the piezo-electric-crystal in short pulses at regular intervals and causes it to vibrate; it triggers the time base circuit and causes a bright spot to move across the CRT screen. The short pulses are of micro-second duration and usually range from 50 – 1000 pulses per second. This is also called pulse rate frequency (PRF). The impingement of short pulses ensures the vibration of the crystal during the pulse period.
2. Transmitter-receiver unit: The transmitter unit generates a voltage pulse, which is applied to the crystal, transducer. The crystal, under the excitation of voltage pulses, executes damped vibrations, which contain natural vibration frequencies of the crystal transducer (of the order of KHz and MHz). This frequency is different from PRF, which is the frequency at which voltage pulses impinge on the crystal to cause damped vibration of the crystal.
3. Synchronizer: In a basic pulse-echo system, the time taken by sonic waves to travel a specified material thickness is compared to the time taken by the pulse to travel a known distance between the *x*-plates of the CRT. This is possible only when the pulse leaving probe and the pulse that excites the *x*-plates are synchronized. This function is achieved by the synchronizer, a clocking mechanism.
4. Sweep generator: The output of the synchronizer is applied to the rectifier circuit so that only positive half of the cycle is conducted, and the negative half is suppressed. The output voltage is applied to the *x*-deflection plates of the CRT so that the bright spot moves left to right. The sweep circuit is also known as the time base circuit.
5. Receiver amplifier: This consists of a multi-stage, broadband radio frequency amplifier followed by a detector and a video amplifier. The video amplifier amplifies the signal to a level where it can be fed to the *Y*-plates and displayed on the CRT screen.

3.6.1 Variables Affecting Ultrasonic Test

A range of factors influence the ultrasonic testing of materials. Broadly speaking, these are classified into two categories:

1. Operator-controlled parameters—such as the equipment and probe selection, the test technique adopted, the couplant used, the speed and the method of scanning and equipment characteristics like linearity of time base, pulse length and frequency used.
2. Parameters beyond the control of operator—such as material properties, surface roughness and curvature, geometry, velocity and attenuation of sound in the material, acoustic impedance, defect characteristics like the size, shape, orientation, depth and acoustic properties of the defect.

Operator-dependent parameters can be controlled effectively. Those beyond an operator's control are:

1. Surface condition: Surface roughness can cause undesirable effects like loss of discontinuity echo; reduction of back surface echo amplitude; increase in the width of transmission echo, resulting in loss of resolving power; distortion of wave directivity properties; generation of surface waves and spurious indications and loss of near surface resolution.
2. Surface contour: The disturbance caused by reflection and refraction can make it difficult to interpret the indications in contoured parts with complex geometry. In such cases, it is helpful to examine the component from two opposite sides, wherever possible. Duplicate measurements at symmetrical points can bring out the similarities or dissimilarities. Often, secondary echoes appear, which are not due to any flaw, as shown in Fig. 3.19A.

   These secondary echoes appear beyond the back-wall echo. Sometimes, a divergent beam traveling a slightly longer, slanted path than the axial beam in the material gives rise to such echoes. These are called 'Ghost echoes' and need not create confusion to the operator, as they appear beyond the back echo.
3. Triangular reflections: While testing solid cylindrical or spherical components with a normal probe, additional echoes may be generated due to a longitudinal wave returning to the crystal after more than one reflection at the side walls. Or before entering the crystal the longitudinal wave gets mode converted to a transverse wave, which is mode converted back to a longitudinal wave after another reflection.

   Either of these cases can occur depending on the angle of incidence and the diameter of the test section, as shown in Fig. 3.19.

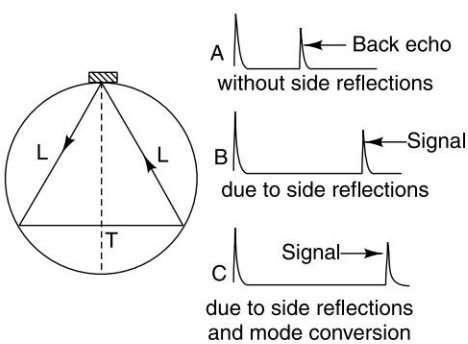


Fig. 3.19 *Triangular Reflections*

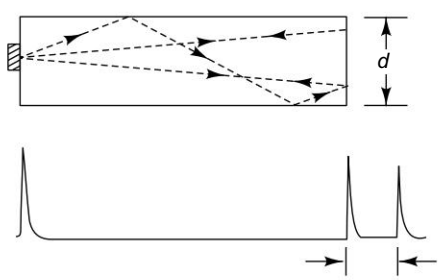


Fig. 3.19A *Secondary Reflection due to Geometry*

4. Fillets and holes: When a cylindrical part with a threaded hole is scanned from the end on surface, a slant beam falling on the sidewall, after reflection from the threaded surface, produces a multi-peaked indication, as shown in Fig. 3.20.

   It is possible to check this problem by damping inside the hole with a wire and observing the damping of the echo.
5. Mode conversion due to geometry: Cylindrical components with shoulders and fillets give rise to mode-converted echoes as follows:
   - A slant beam hitting the fillet directly results in a fillet echo as Fig. in 3.21.
   - A slant beam hitting a shoulder is mode-converted as a transverse wave and reaches the opposite fillet. Here, the wave is again mode-converted and reaches the probe, resulting in an echo *m*. This phenomenon of mode conversion at angular incidence needs to be understood clearly, so that there are smaller chances of misinterpretation of echoes.

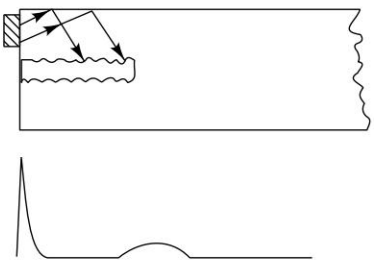


Fig. 3.20 *Reflection from a Threaded Hole*

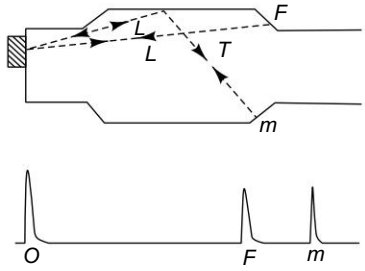


Fig. 3.21 *Reflection due to Fillets*

- Mode conversion can occur in components with a threaded hole as shown in Fig. 3.22.

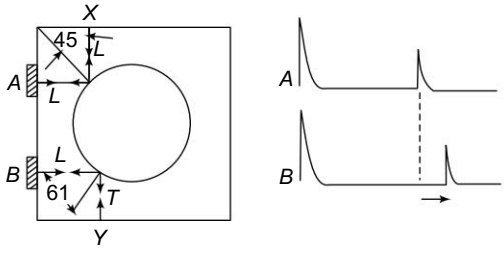


Fig. 3.22 *Reflection from Bore Wall*

In position *A*, the angle of incidence is 45° and after reflection, the beam retraces its path.
In position *B*, the angle of incidence is 61° for a steel component. The longitudinal wave gets mode-converted and travels to face *Y* as a transverse wave. The converted transverse wave travels back to the bore surface, where it is mode-converted as a longitudinal wave and reaches the probe. The resulting signal is located further away from the signal at *A*.

To evaluate echoes resulting due to shape and geometry of the part, it helps to:

- Mark the echo positions. Material and geometrical considerations suggest whether the reflections are from possible defects or not

- Study a symmetrical location on the same test specimen or on a symmetrical component. Use angle probes, where possible, to confirm findings
- Make accurate measurements of the location of the echo

6. Material characteristics: Material properties like density, elastic modulus, metallurgical structure and structural in-homogeneities resulting from lay-up and cure operations in fiber-reinforced composites influence ultrasonic attenuation and acoustic impedance. Attenuation determines the depth to which an ultrasonic test can be carried out. Attenuation loss also influences the amplitude of the reflected signal from defects located at different depths in the material. The acoustic impedance of two materials on either side of an interface determines the extent of reflection and transmission of ultrasonic energy from one medium to the other.
   The reflected and transmitted energy depends on the ratio of impedance of the second material to the impedance of the first material. The sound transmitted through the interface decreases as the impedance mismatch increases.
7. Flaw characteristics: Ultrasonic reflection from a flaw depends on the size, shape, orientation and acoustic properties of the flaw. The acoustic properties of the flaw also determine the amplitude of reflection. A flaw filled with air produces a good reflection, whereas a flaw filled with organic matter or oxide inclusion gives a weak signal. In the former case, impedance mismatch between the material and the air inside the flaw is high; in the latter case, it is low. Further, a flaw with a smooth surface reflects well while a flaw with a rough surface reflects weakly.
   Any flaw with a good reflecting surface, oriented at right angles to the beam direction produces a signal with good amplitude. Unfavorable orientation of large flaws does not allow the beam to reach the back-wall. This situation may lead to the absence of a flaw as well as a back-wall signal. Angle probes are used in such a situation.
8. Acoustic coupling: In a direct contact test, the degree of acoustic coupling depends on the surface finish and the acoustic impedance of the intervening medium. Oils of different viscosities are used here. Thicker oils or greases are used both for vertical and horizontal surfaces of the components. The use of a different couplant can cause a variation in results even for similar tests on a given sample. To minimize this, probing conditions must be standardized. Sometimes, while using shear wave probes with a thick fluid as couplant, there may be a faint surface wave indication due to accumulated couplant in front of the probe.
9. False indications: These are caused due to noise or reverberation in the test specimen. Sometimes, an apparent discontinuity moving in a horizontal plane is probably due to other heavy-duty equipment located nearby. This indication can be distinguished from a defect indication, as it is irregular and not synchronized with the time base.
   The indication due to reverberation is caused where a material with low attenuation is tested at a high pulse frequency. This occurs when the test material does not attenuate the initial sound pulse before the next pulse is transmitted. The result is apparent discontinuity indication, synchronized with the sweep line or the time base. Such a disturbance cannot be eliminated completely but can be reduced to the point that a correct interpretation of the valid discontinuity becomes possible by reducing the gain to the required level.
10. Interpretation of indications: All types of defects, discontinuities or material, in-homogeneities, produce echoes, the amplitude of which depends, among other things, on their specific acoustic impedance. The information available on the CRT during the test by *A*-scan presentation is:

- The amplitude of the signal characterizing the size of the discontinuity in the path of the ultrasonic beam.
- The loss of back reflection amplitude.
- Location of discontinuity from the scanning surface.

Various *A*-scan indications corresponding to particular defects can be characterized as follows:

1. Spherical defects (gas hole type): An echo from a single defect with dimensions greater than the selected standard defect size, is sharp and clear. A group of gas holes gives rise to an echo representing a superimposed multi-peaked signal and the trace appears jagged.
2. Volume defects of irregular shape (inclusion type): Non-metallic inclusions give rise to an echo trace that is forked or broadened (where resolution is poor). When the probe is rotated around the defect, the echo does not disappear, but its shape varies.
3. Sharp linear defects (crack-like): Linear defects like cracks give a sharp and clear signal. The amplitude can vary when the probe is moved around the defect. For long cracks, the amplitude decays when the probe is moved in a circular path with the flaw in the center.
4. Lack of penetration in welds: Echoes from this type of defect give a clear and sharp signal. The signal disappears when the probe is moved round in a circle with the defect at its center. When lack of penetration occurs at the root, the maximum reflected signal occurs at half the skip distance from the weld center. If the flaw echo remains stationary over a long distance of the scan, the lack of penetration is considerable. If the probe is moved in the direction perpendicular to the axis of the weld and the echo disappears rapidly, then the defect is small and shallow. Often, the study of echo formation and its movement over the CRT screen, while manipulating the probe, provides useful information.

3.7 Ultrasonic Testing

3.7.1 Basic Methods and General Considerations

Ultrasonic testing depends on the nature of the product, its manufacturing process, the surface condition, geometry and accessibility of the scanning area.

There are three basic test methods commonly used in industries: pulse echo, through transmission and resonance.

1. Pulse echo test method: Here, short pulses of ultrasonic waves are transmitted in the material under test. These pulses are reflected from discontinuities in their path or from any boundary of the material. The reflected waves (or echoes) are received by the same transducer and are displayed on the CRT, which provides the following information:
   - The relative size of the discontinuity in terms of the amplitude of the signal displayed on the CRT
   - The depth of the discontinuity on the CRT time base scale, which is appropriately calibrated in terms of known material thickness

     In this method, a single transducer is used both as transmitter and receiver of the waves. Sometimes two transducers are used, one as transmitter and the other as receiver

The main advantage of this method is that only one surface of the test object is required for testing and the method is capable of providing size as well as depth location of the discontinuity. However, a limitation is that the material immediately below the transducer contact surface, within the near zone, cannot be examined unless the appropriate delay shoe is attached to the transducer in contact testing or a suitable length of water column is provided in immersion testing. Figure 3.23 illustrates this method

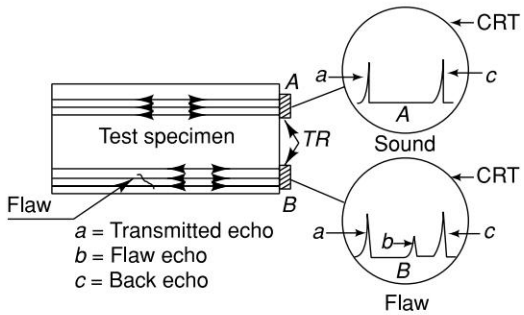


Fig. 3.23 *Pulse Echo System*

2. Through transmission method: Two transducers are used here, one as transmitter, the other as receiver. Short pulses of waves are transmitted into the material. The test method requires access to two nearly parallel surfaces of the test object. The receiver transducer is aligned properly with the transmitter transducer on the opposite side of the test object to pick up the ultrasonic waves passing through the material. The soundness or quality of the test material is evaluated in terms of energy lost as the ultrasound travels through the material. The presence of a discontinuity is indicated by variations in the energy amplitude. A significant reduction in energy amplitude indicates a discontinuity. The main disadvantage of this method is its inability to locate the defect. Misalignment of the search unit can also create an interpretation problem. Figure 3.24 illustrates the test system.

   An advantage of the through transmission system is better near surface resolution.

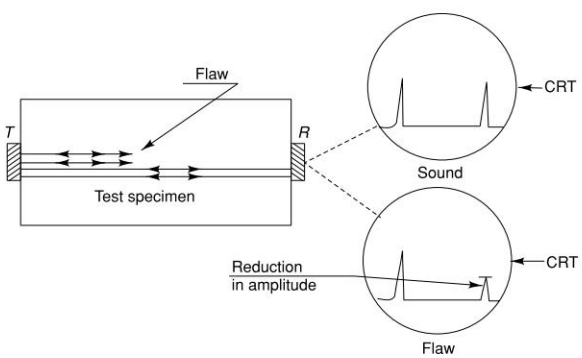


Fig. 3.24 *Through Transmission System*

3. Resonance system: This system makes use of the resonance phenomenon to measure material thickness and to determine the bond quality of a test object. Continuous longitudinal waves are transmitted into the material and the wave frequency is varied until standing waves are set up within the specimen, causing the specimen to vibrate at greater amplitude. At resonance, the specimen thickness is equal to one half or multiples of a wavelength. Resonance is detected by an indicator device and is presented on the CRT screen as a 'pip' as shown in Fig. 3.25.

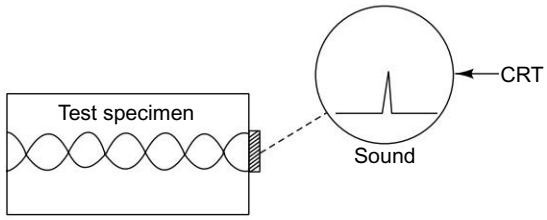


Fig. 3.25 *Resonance System*

A disadvantage of this system is that the accuracy of the test reduces as the material thickness increases.

Contact and Immersion Mode of Testing

Ultrasonic tests are conducted either in contact mode or in immersion mode.

In the contact mode of testing, the transducer is kept in contact with the test object with a couplant like water, oil or grease applied between the test surface and the transducer. The energy reflected from the boundary wall or the flaw is displayed on the CRT. This method is widely used for manual inspection. Straight as well as angle beam probes are used. A single transducer acts as transmitter as well as receiver for ultrasonic energy. Sometimes two transducers are used for this. Figure 3.26 illustrates the contact mode arrangement.

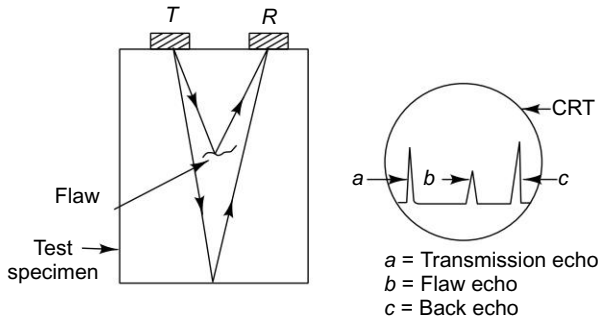


Fig. 3.26 *Two-probe Pulse Echo System*

In the immersion method, the test specimen and the leak-proof transducer are immersed in a liquid, usually water. The liquid acts as a couplant. This method provides testing flexibility. The transducer can be moved under water at any desired angle. Further, the transducer does not contact the specimen and is therefore not subjected to wear. Higher frequencies can be employed, enhancing defect detection efficiency. Immersion testing is employed for high speed and automatic scanning. Figures 3.27 and 3.28 illustrate the immersion pulse-echo normal probe and immersion pulse echo angle probe methods.

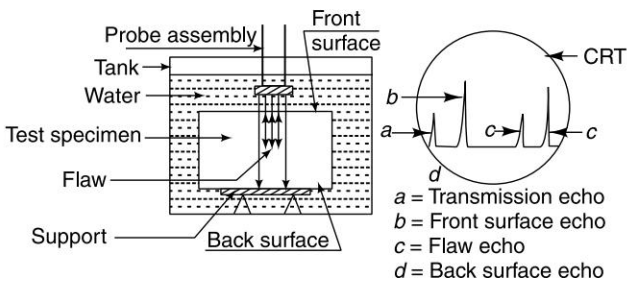


Fig. 3.27 *Immersion Pulse Echo Method*

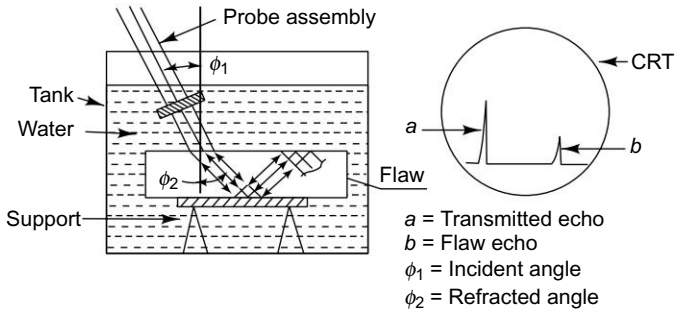


Fig. 3.28 *Immersion Angle Beam Method, Using Longitudinal Waves*

It is important to appreciate that shear waves cannot be used in a fluid; therefore, only longitudinal waves are used and introduced into the medium at an angle, with the help of manipulators. Longitudinal waves entering the medium get mode-converted as shear waves at an angle. After reflection from any defect or boundary, the transverse wave gets mode-converted and travels back to the transducer as a longitudinal wave.

In the through transmission immersion technique, the specimen is immersed in a liquid couplant, usually water. A separate transmitter and receiver are axially adjusted through manipulators. Ultrasonic energy is transmitted into the specimen, which is mounted on a special fixture, for easy adjustment. Any defect in the path of the ultrasonic beam causes a shadow and hence, a reduction in the intensity of the beam. Figure 3.29 illustrates the test system.

Further, to reduce the difficulty in interpretation, the water path, that is the distance between the transducer and the front surface of the specimen, should be selected such that the ultrasonic transit time in the liquid column is greater than the ultrasonic transit time between the front and back surfaces of the test material.

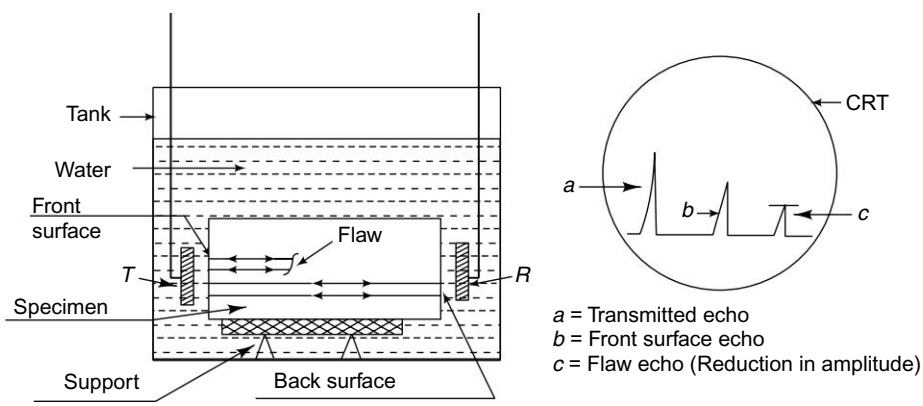


Fig. 3.29 *Through Transmission Immersion System*

Angle Beam Testing

An ultrasonic beam is transmitted into the test specimen at an angle to the test surface. To achieve this, the piezo-electric element is mounted on a plastic wedge at the desired angle. The flat edge of the wedge is placed on the test surface as shown in Fig. 3.30.

When the angle of the incident beam is other than normal to the test surface, refracted longitudinal and shear wave components are produced due to mode conversion. Longitudinal waves are originally produced in the wedge but it is possible to have either longitudinal or shear waves in the test specimen. Both may be present at the same time depending upon the angle of the wedge.

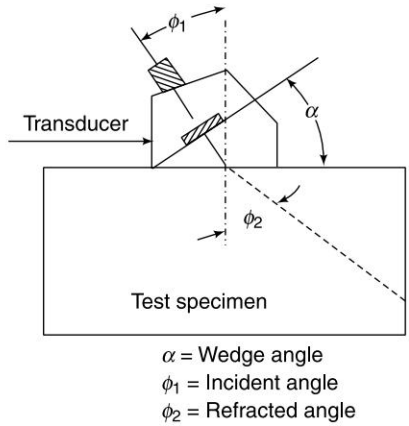


Fig. 3.30 *Angle Beam Technique*

As the angle of incidence is increased to the second critical angle, when the shear wave travels parallel to the surface, a surface wave mode is developed in the medium. This wave can penetrate the medium to the extent of one wavelength. This wave pattern is known as 'surface wave' or 'Rayleigh wave' and its velocity is about 90% of the velocity of shear waves. These waves are used for detecting surface discontinuities in the contact mode of testing. The waves follow the contour of the test specimen around fillet radii and other irregular surface features. Figure 3.31 illustrates this.

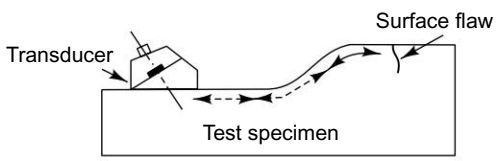


Fig. 3.31 *Surface Wave Testing*

In very thin sheets, the angular incidence of the sound beam and mode conversion at the interface produces plate or lamb waves. The velocity of these waves depends on the type of material, the frequency, and the velocity in the wedge material, the angle of the wedge and the plate thickness. Various applications of these waves are given in Table 3.2.

TABLE 3.2 *Application of shear, surface and plate waves*

Testing Method	*Typical Applications*
Shear waves	Inspection of welds, plates, pipes, tubing and complex geometry forging and castings
Surface waves	Inspection of surface defects (e.g. heat treatment cracks, fatigue cracks, tool marks, stress raisers, etc.)
Plate waves	Detection of laminations in thin materials, lack of bonding in composite materials

3.7.2 Testing of Products

Castings

Ultrasonic testing of castings is limited to the detection of large isolated discontinuities such as voids, inclusions, cracks and regions of segregation, dispersed coarse porosity and coarse grain structure. The application of ultrasonics to castings is limited due to their size, shape, thickness, surface roughness and coarse grain structures. The inspection of flat castings with parallel sides with ultrasonic is simple, as in testing cast blooms for primary and secondary piping for cropping before further operations.

Wrought Products

Wrought products generally have uniform geometrical sections—round, square or rectangular. Figure 3.32 shows a square section having a defect and causing a signal without any ambiguity in interpretation. But in the same specimen, if the defect happens to be at a larger inclination to the beam, it may not give a defect indication other than some reduction in the back signal amplitude. Such cases require scans from different directions to explore the presence of a defect and to assess its nature and size. Normally, such square and rectangular sections are scanned in two directions, preferably at right angles to each other. Figure 3.33 shows the scan of a round section of a wrought material containing a forging burst. The defect indication shows up when the probe is in position *B*. The defect is not shown when the probe is in position *A*, because the plane of the defect is parallel to the sonic beam axis. In such cases, the scan path should cover at least 120° (preferably 180°), as indicated by the arrow, to cover all probable orientations of defects.

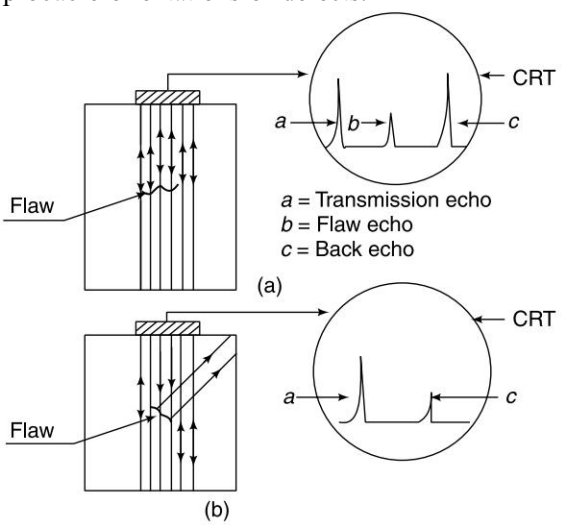


Fig. 3.32 *Simple Regular Section*

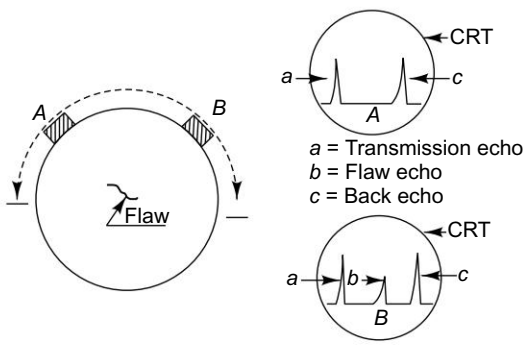


Fig. 3.33 *Round Section*

Forgings of complicated shape, it may not be possible to scan 100% of the surface. In such cases, the best way is to test the billet thoroughly for any defect and, in a multistage forging operation, to test the product at convenient stages. In the final forged condition, only some areas may be amenable to an ultrasonic check.

Figure 3.34 shows the cross section of a forging where cracks originate from the inner radius, invariably at an angle of 45° to the lug. To detect this type of crack, a 45° angle beam probe is used, as shown. In the absence of a crack, the ultrasonic beam follows a path as shown at *A* and after reflection from the inner wall, may not return to the transducer, resulting in no signal. When a crack is present, the ultrasonic beam is intercepted by the crack, retraces its path and produces a defect signal as indicated in *B*.

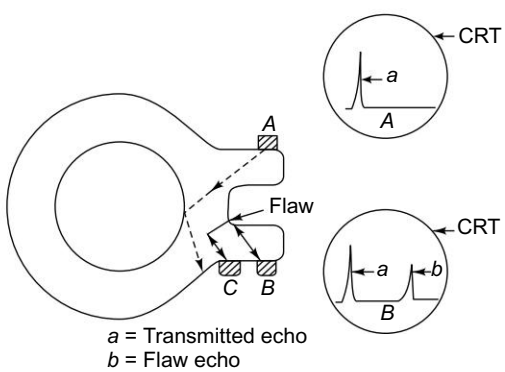


Fig. 3.34 *Testing of Selected Location*

Figure 3.35 shows an actuator housing, which is subjected to fluctuating hydraulic pressure, leading to fatigue failure. Fatigue cracks appear as shown at *B*. Here, the geometry of the component permits the use of a 60° angle probe to detect any crack in its initial stage of formation. In the absence of a crack, as shown at position *A*, there is no defect signal. In the presence of a crack, when the probe is positioned at *B*, the ultrasonic beam is intercepted by the crack, resulting in a defect signal. This type of angle beaming of critical areas is found to be useful in the detection of defects initiated during service.

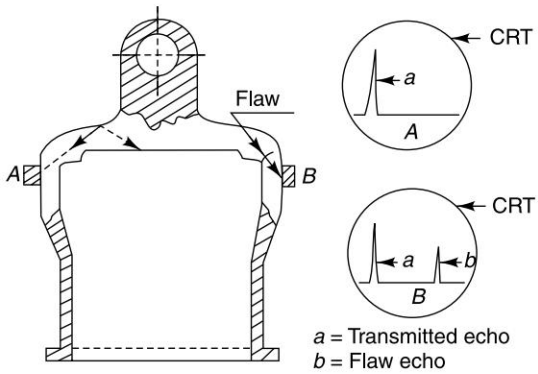


Fig. 3.35 *Testing of Selected Locations of a Housing*

Weldments

Welds are ultrasonically tested either by the straight beam or the angle beam technique. The angle beam technique is commonly used, as the straight beam testing requires weld beads to be ground to get a flat scanning surface. Apart from being expensive grinding of weld beads is not always permissible from design considerations. Welds are usually tested at frequencies 1, 2, 2.5 and 5 MHz with varying angles like 35°, 45°, 60°, 70° and 80°. The procedure adopted is as follows:

(a) Determination of skip distance and half skip distances. Skip distance *S* is the distance between two nodes and is given by $S = 2t \tan\phi$,
where ϕ = refracted angle, *S* = skip distance and *t* = specimen thickness

(b) Two lines are drawn from the central axis of the weld bead, one at a distance of *S*/2 and the other at a distance *S*, parallel to the weld bead.

(c) Now the angle probe is moved for skip distance *S* to half skip distance *S*/2, with a swivel motion of the probe at '*A*'. When the probe is at *S* the top of the weld section is scanned; when it is at *S*\2, the root of the weld is scanned; in between *S* and *S*/2, the intermediate weld sections are scanned. Any defect in the weld section will intercept the ultrasonic beam and make it retrace its path, thereby causing a signal on the CRT screen. Figures 3.36 and 3.37 illustrate this.

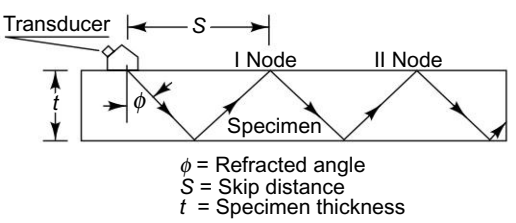


Fig. 3.36 *Path of Shear Wave*

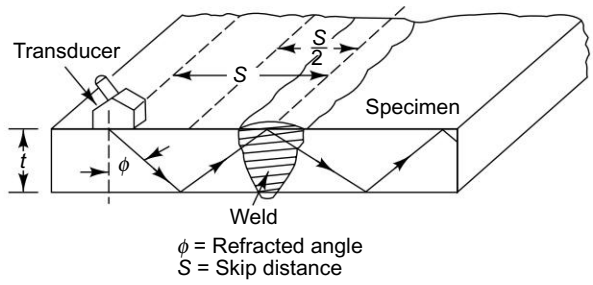


Fig. 3.37 *Testing of Welding*

Testing of Fillet Welds

Ultrasonic testing is employed extensively for butt welds, but some fillet welds can also be tested by this method. However, due to the complexity of joints, all fillet welds are not amenable to ultrasonic testing. Figure 3.38 shows the testing of a double fillet weld, using a normal probe from a horizontal member of the weld. Scan *A* shows a multiple reflection pattern from the horizontal member; scan *B* indicates a sound weld with a weak back wall echo; scan *C* indicates a defective weld, showing a good defect echo and a weak back echo. Figure 3.38 shows the testing of a single fillet weld using an angle probe.

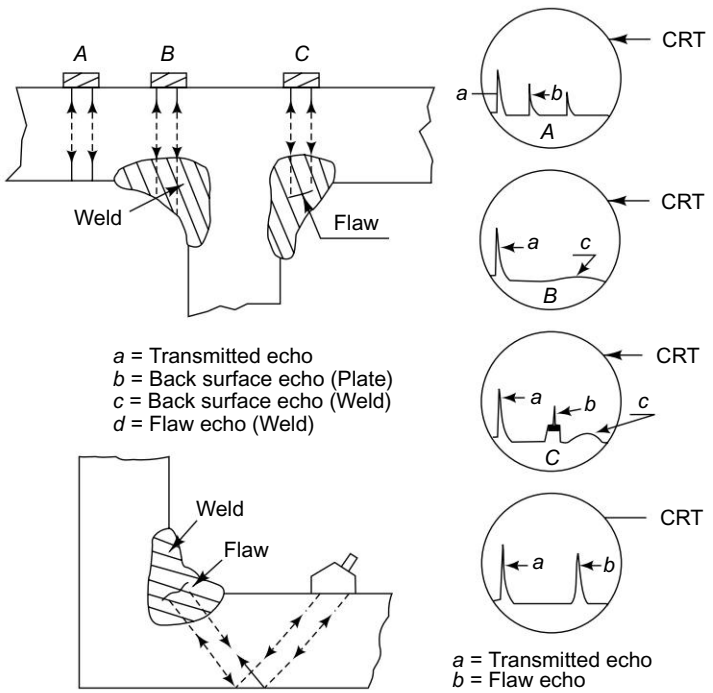


Fig. 3.38 *Fillet Weld Testing Using Angle Probe*

Immersion Testing of Welded Tube

Figure 3.39 illustrates the immersion testing of weld tubes. In weld testing, it is usually desirable to generate shear waves in the test object. To achieve this, the transducer is tilted through an angle of incidence between 15° and 33°. In shear wave testing, a small and poorly defined reflection for the entry surface and a strong reflection from the crack in the test specimen are shown on the CRT screen.

Much of the sound wave is reflected from the surface. A fraction of the sound wave that enters

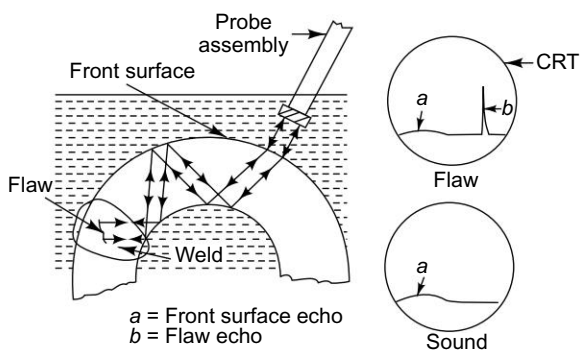


Fig. 3.39 *Immersion Testing of Welded Tubes*

the specimen travels around the circumference until it strikes a discontinuity that will cause a reflection. In areas where no discontinuity is present, only a small front reflection is shown.

Two Probe Method (Pitch Catch)

Weld defects perpendicular to the plate surface and weld axis or defects whose plane is parallel to the weld axis and perpendicular to the plate surface are examined using two probes. Figure 3.40 shows the typical location of two such defects detected and evaluated by a pair of probes T_1T_2 and T_3T_4. This type of testing requires both probes to be coupled on a guiding mechanism for effective working.

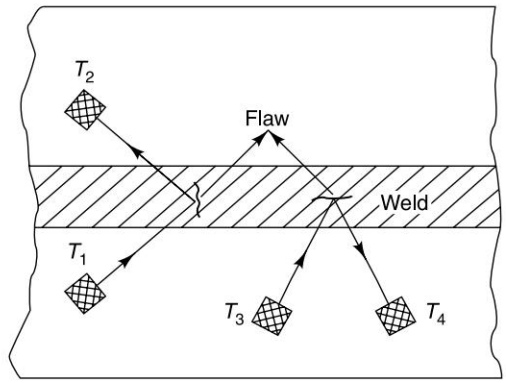


Fig. 3.40 *Pitch Catch Method of Using Two Angle Probes*

Resonance Method for Testing Thickness

A test component is said to be in resonance when its thickness is an integral multiple of half wavelengths of the applied frequency. Continuous compression waves of variable frequency are transmitted into the material to establish a standing wave, creating the condition for resonance. Figure 3.41 shows the standing wave pattern due to resonance.

If f is the fundamental resonant frequency and V is the velocity of the wave in the test material, then

$$f = \frac{V}{\lambda} \qquad \text{or } \lambda = \frac{V}{f}$$

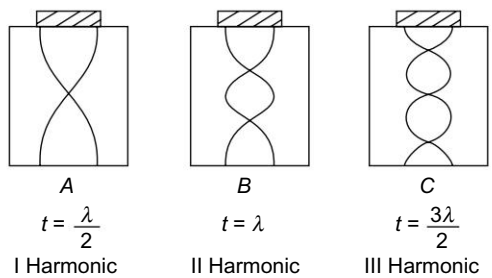


Fig. 3.41 *Standing Wave Pattern due to Resonance*

At resonance, $t = n\lambda/2 = nV/2f$

The thickness of the component can be calculated from this relationship. Since resonance can occur at any of the harmonic frequencies and the difference between any two adjacent harmonies gives the fundamental frequency, the following relationship is used to calculate thickness.

$$t = \frac{V}{2(f_{n+1} - f_n)}$$

where f_{n+1} = resonant frequency at the $(n+1)^{th}$ harmonic and f_n = resonant frequency at the n^{th} harmonic.

Direct contact as well as immersion resonance methods are used for thickness determination.

Resonance methods are used for thickness gauging, corrosion inspection, bond testing composites and detection of gross defects in thin materials.

3.7.3 Calibration Standards

Interpretation of ultrasonic test indications, either from flaws or material conditions, owing to the fabrication process, is based on indications from an appropriate reference standard. Reference standards are made of a material with density and acoustic impedance similar to the test material. Reference standards (also called calibration standards), are designed to suit the application requirements of a product. Generally, the purpose of calibration related to the ultrasonic testing of materials is:

- To ensure consistent performance of the ultrasonic test instrument
- To check the sensitivity, resolution and characteristics of the ultrasonic probe (search unit)
- To evaluate defects for their size and location
- To assess the homogeneity of the material and the state of local or volume distribution of stresses
- To provide a common basis for expressing the test results

Calibration blocks may be divided into three groups:

- Blocks for performance evaluation of an ultrasonic test system consisting of an ultrasonic test unit and a search unit
- Blocks with flat bottom holes (artificial reflectors)
- Regular components with simulated or natural defects

Blocks for Performance Evaluation of Test Systems

Two calibration blocks are widely used, the British calibration block and the International Institute of Welding Block (IIW Block). Figure 3.42 shows a British calibration block.

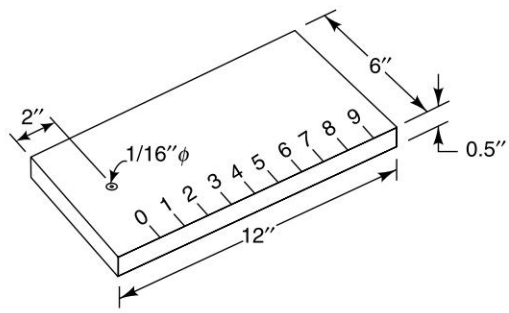


Fig. 3.42 *British Calibration Block*

British Calibration Block

The longitudinal edge of one face of this block is graduated in 0.2″ divisions. The block has a 1/16″-diameter drilled hole two inches from one edge. The center of this hole coincides with the zero mark of the graduations. The block material is a killed open hearth or electrical furnace mild steel in normalized condition with a surface finish of 250 micro inches and an overall size of 12″ × 6″ × 1/2″.

This block is used for checking:

- Linearity of the time base
- Calibration of any auxiliary scale, and
- Standardization of working sensitivity

Checking linearity of time base:

The probe is kept at various positions on the block to get half skip, full skip and one and half skip distance echoes from markings 1, 2 and 3 respectively, as shown in Fig. 3.43. Equal echo spacing indicates time base linearity.

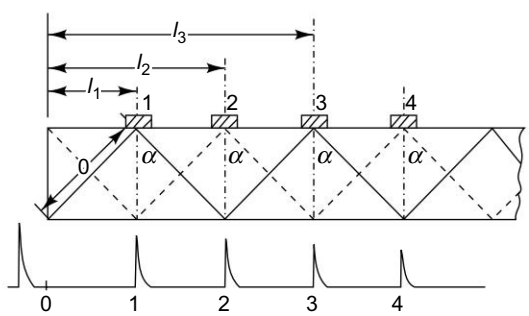


Fig. 3.43 *Linearity of Time Base*

From the geometry of the figure we have:

$$\text{Path } P = (l_2 - l_1) \text{ cosec } \alpha$$
$$= (l_3 - l_2) \text{ cosec } \alpha$$
$$= (l_x - l_{x-1}) \text{ cosec } \alpha$$

From this, it is possible to calibrate the time base in terms of length.

Correction of zero point: If the time base is linear, the distance between the first and second back echos is measured and marked on the CRT screen to the left of the first back echo. This gives the correct zero point as shown in Fig. 3.43. The distance between this zero point and the initial echo is the zero error.

Setting of working sensitivity: The hole is used as an edge reflector and the angle beam probe is directed towards it. The gain is set to obtain a specific readable echo light and the probe is moved forward and backward to obtain maximum amplitude. The gain value, maximum echo height and the probe position from the center of the hole are noted. At this setting, data can be checked later for any deterioration in sensitivity.

International Institute of Welding Block (IIW Block)

This block was developed by the International Institute of Welding and is shown in Fig. 3.44. The block is used for checking:

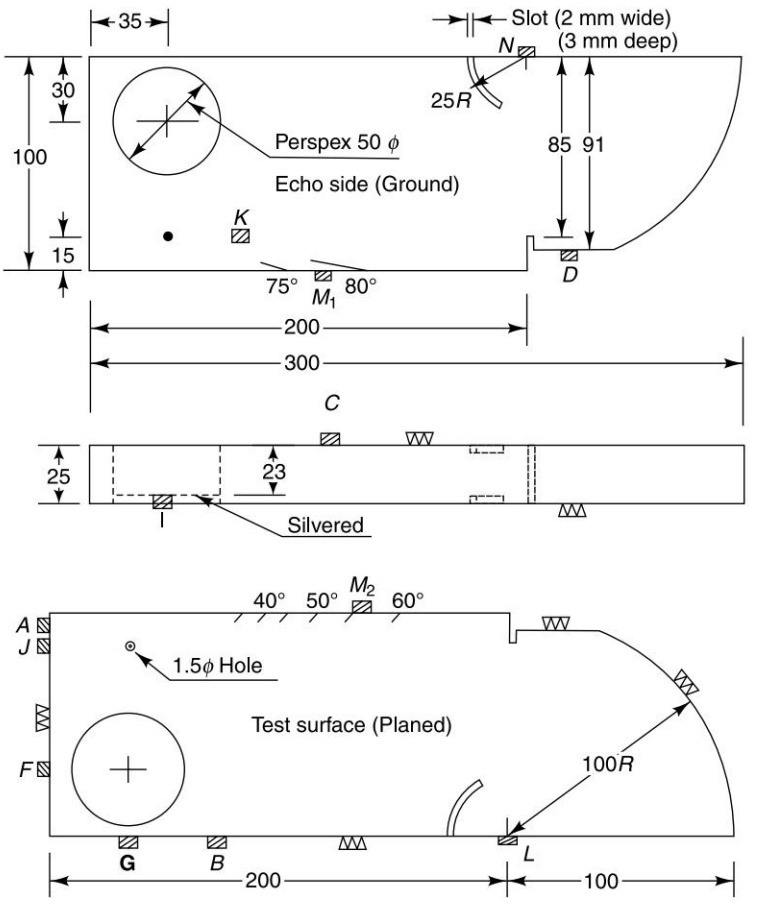
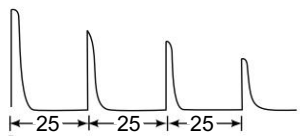
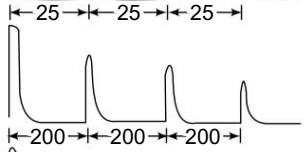
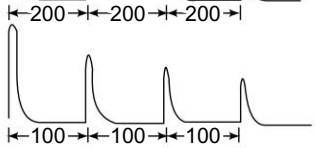
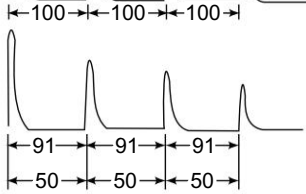
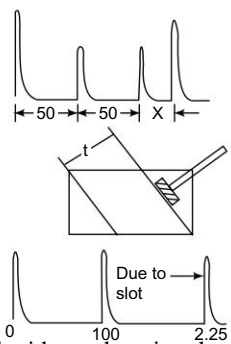


Fig. 3.44 *IIW Calibration Block*

- Linearity of time base
- Scale calibration
- Correction of zero error
- Probe index
- Probe angle
- Resolution
- Sensitivity and
- Dead zone

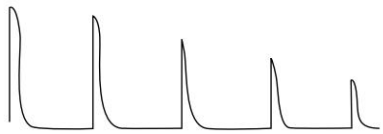
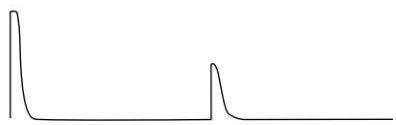
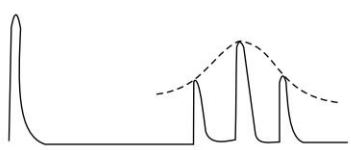
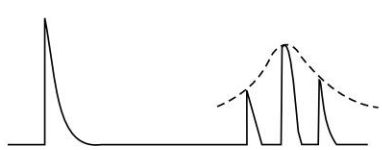
The probe positions for various calibrations and ultrasonic indications are shown in the following figures and tables.

TABLE 3.3 *Probe positions and ultrasonic indications for various calibrations*

Equipment Characteristics	*Probe Position*	*Indication on CRT*
1. Linearity of Time base (a) *Longitudinal wave:* Range < 200 mm	C	
Range > 200 mm	A	
	B	
(b) *Shear Wave:*	D	
Note: 91 mm of longitudinal wave travel in steel is equivalent to 50 mm of shear wave travel.		
2. Zero error correction (Angle probe)	N	
Note: Calibration same as at probe position D. Angle probe used without changing the range. Reading 'X' on CRT is due to perspex travel distance '*t*' which gives zero error.		

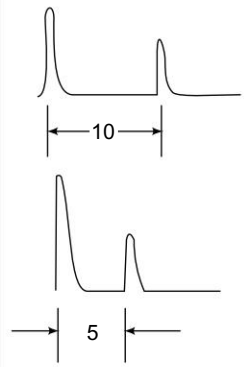
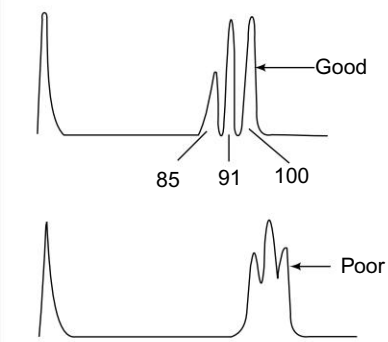
(*Contd*)

(*Table 3.3 Contd*)

Equipment Characterstics	*Probe Position*	*Indication on CRT*
3. Working sensitivity (a) *Normal probe* (i) High power	I	
(ii) Medium and low power	J	Mark the setting, number of echoes and height of last echo 
(b) *Shear wave probe*	K	Mark the height of 1.5 mm hole echo 
Note: Get the maximum height of the echo from the edge of the hole and note the probe distance from the hole, the gain setting and the echo height for maximum amplitude. Repeatability of sensitivity is ensured if the echo position and height are reproduced with the same equipment setting and testing condition, at a later stage.		
4. Probe index	L	 Position of the probe coinciding against the slot for a maximum height from 100 mm curved surface
5. Angle of refraction	M_1 (45° – 70°) from 50 mm ϕ hole M_1 (75° – 80°) from 1.5 mm ϕ hole	

(*Contd.*)

(*Table 3.3 Contd*)

Equipment Characteristics	*Probe Position*	*Indication on CRT*
6. Dead zone	F G	
7. Resolution (Normal probe)	L	

Miniature Angle Beam Probe Calibration Block (DIN 54122)

This block is used for calibration during fieldwork. Angle beam probes are used to check time base linearity, probe angle, probe index and range setting.

With the probe facing the 25 mm radius, echoes appear at 25 mm, 100 mm, 175 mm, etc. When facing the 50 mm quadrant, the echoes appear at 50 mm, 125 mm and 200 mm. This establishes the linearity of the time base. The probe angle is checked using a 5 mm diameter target hole, provided in the block.

Various probes used for weld inspection can be checked for angle, probe index, etc. using this target hole. Figure 3.45 shows this block.

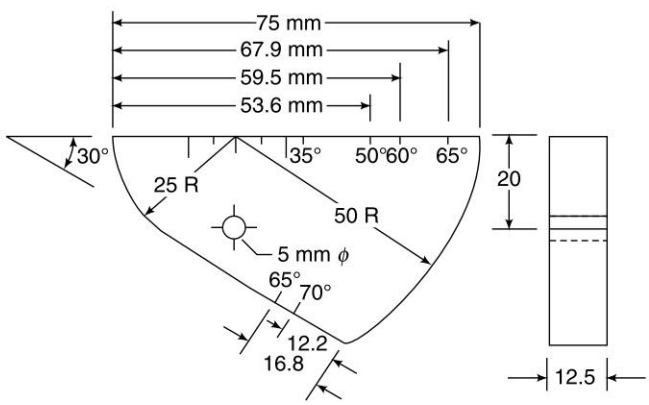


Fig. 3.45 *Miniature Block* (*DIN 54122*)

Blocks with Flat Bottom Holes

Flat bottom hole blocks, developed by ASTM (see Fig. 3.46) consist of a basic set of ten blocks and a distance amplitude set of 19 blocks. The basic set consists of one block with 3/64" flat bottom hole at a metal distance of 3", 7 blocks with 5/64" flat bottom hole having metal distances of 1/8", 1/4", 1/2", 3/4", 1½", 3" and 6" and 2 blocks with 6/64" diameter flat bottom hole having metal distances of 3" and 6".

A = Metal travel distance ± 0.015 inch

B = Hole depth 3/4 inch nominal ± 1/16 inch

C = (a) 2.00 inch diameter ± 0.030 inch for distance 0–6 inches

(b) 2.50 inch diameter ± 0.030 inch for distance 6–12 inches

D = Hole diameter tolerance ± 0.001 inch

E = Surfaces to be flat within 0.005 inch and parallel within 0.001 inch

F = Holes must be straight and perpendicular to the test surface within 0°20′

G = Hole bottom must be flat within 0.001 inch per 0.125 inch

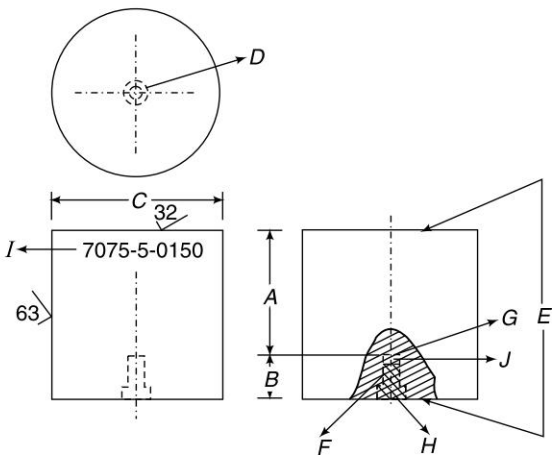


Fig. 3.46 *ASTM Flat Bottom Reference Block*

H = Counter bore, minimum of 0.125 inch larger than test hole and minimum 0.125 inch deep. Sealed with teflon plug to half hole length. The remainder of the hole is to be filled with epoxy sealant

I = Identification

7075 = Aluminum alloy (ALCOA)

5 = Hole size 5/64 inch diameter.

0150 = Metal travel distance 1.50 inch

J = Adequate air gap

Amplitude-area Linearity

With a particular equipment setting for gain frequency, probe and coupling, the amplitude or echo height from the reflector with an area corresponding to 3/6", 5/64" and 8/64" diameter flat bottom hole is obtained and a graph is plotted with the area on the *X* axis and Amplitude on the *Y* axis. A typical curve is shown in Fig. 3.47.

Figure 3.47 shows the linearity between the area of the reflector and the amplitude of the reflected signal for a given metal distance.

Distance-amplitude Relationship

This relationship shows the variation in amplitude of reflected energy from a given size of reflector for different distances. A graph is plotted between the amplitude of reflection from a given diameter flat bottom hole and different metal distances for specified test conditions. A typical graph is shown in Fig. 3.48.

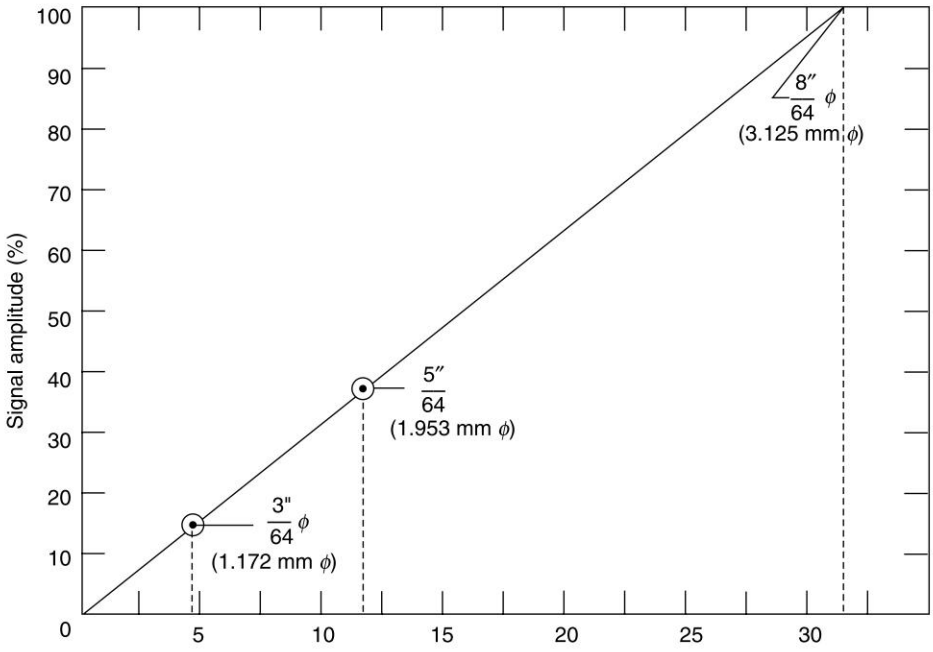


Fig. 3.47 *Area-Amplitude Curve*

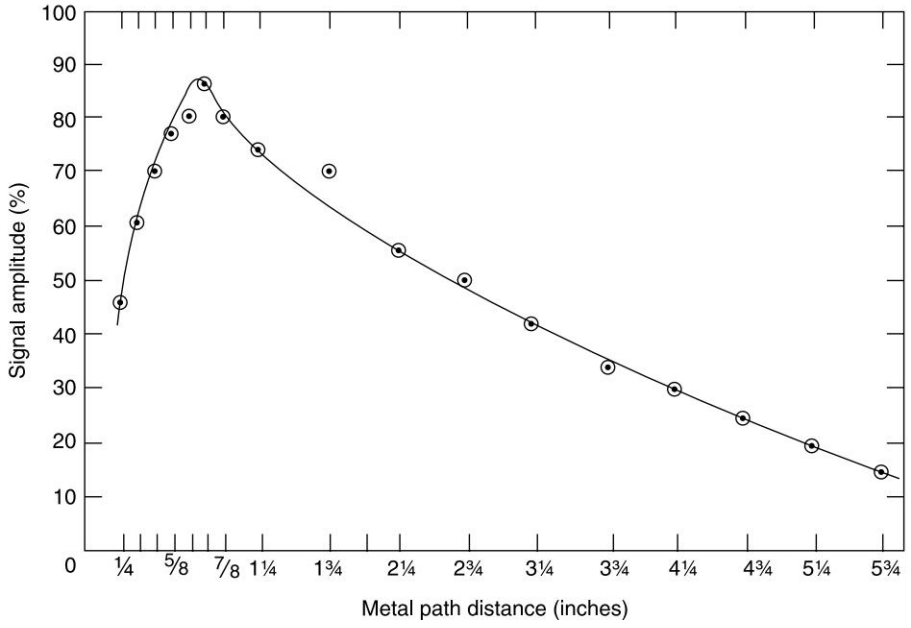


Fig. 3.48 *Distance-Amplitude Curve*

The relationship indicates that for the same area of reflector, as the distance of the target increases, the echo amplitude decreases due to attenuation losses.

Beam Plotting and Evaluating Beam Divergence

A minimum of two standard blocks with the same flat bottom holes of diameter, say 5/64", with varying metal distances are used. With a particular equipment setting and a given probe, the maximum peak from one of the blocks with a metal distance of, say, 3" is obtained. The peak height is kept at slightly less than the vertical saturation limit. The probe is now moved to the right of the scanning surface until the echo amplitude drops to 20 db. The center of the probe position is marked X_1.

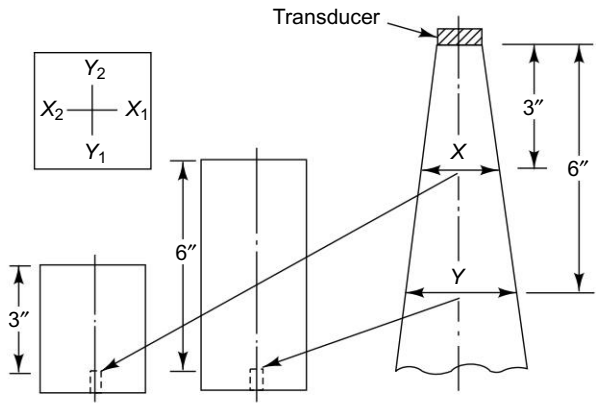


Fig. 3.49 *Beam Plotting Using Flat Bottom Hole*

The probe is now moved to the left until the echo amplitude drops to 20 db. The mid position of the probe is marked X_2. The maximum amplitude is again obtained. The probe is then moved towards a perpendicular direction to the line $X_1 - X_2$ and positions Y_1 and Y_2 are obtained for 20 db drop points.

The average of the distance between $X_1 - X_2$ and $Y_1 - Y_2$ is the beam diameter of a metal distance of 3". Similarly, the beam diameter for a metal distance of 6" is measured. With these two diameter values, the beam profile for the probe can be drawn as shown in Fig. 3.49.

3.8 Interpretations and Guidelines for Acceptance/Rejection

Interpretation implies analyzing the indications on the CRT screen with regard to the position, shape and amplitude of the echo signals and correlating them to the depth, nature and size of the flaw in the test component.

3.8.1 Determination of the Size and Shape of Flaws

The appearance of a flaw echo depends upon the size, nature and orientation of the flaw within the specimen. A flaw is considered large if its cross-section is larger than that of the sonic beam at the flaw location. The size of such a flaw is determined by mapping the projected contour on the scanning surface, observing both the flaw echo and back-wall echo. The size of the flaw thus obtained is usually more than the actual flaw size, due to beam divergence. Realistic flaw mapping is possible only when the orientation of the flaw is normal to the sonic beam.

A small flaw, whose size is smaller than the diameter of the probe crystal, is determined by comparing the flaw signal amplitude with the signal amplitude from a known size target.

Some information regarding the shape of the flaw can be obtained by observing the shape and height of the echo (echo dynamics) on the CRT screen when the probe is manipulated. A steep rise of the echo even for a small amplitude, generally, is indicative of a lamellar flaw; this happens when the flaw surface is perpendicular to the sonic beam. If the plane of the flaw is not perpendicular, the echo formation is slow and gradual. If the flaw is of irregular shape, it results in a complex and multi-peaked signal. By probe manipulation it is possible to align the sound beam in a preferred direction. Echo formation and the change of its shape due to sonic beaming, for linear and irregular flaws, is illustrated in Fig. 3.50.

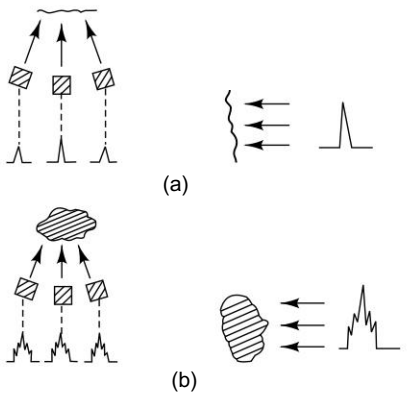


Fig. 3.50 *Echo Dynamics for Different Flaws*

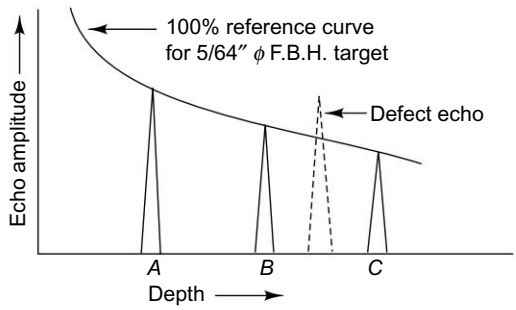


Fig. 3.51 *Flaw Assessment by Distance-Amplitude Curve Method*

Determination of Flaw Size (Flaw Smaller than Probe Diameter)

Distance-amplitude Curve Method

If the acceptance limit is, say, a 5/64" diameter flat bottom hole, then a minimum of three blocks of 5/64" diameter flat bottom hole with different metal distances are selected. With a specific gain setting, a readable target echo as well as a back echo are obtained. As the target distance increases, the echo amplitude decreases and if the peaks of the echoes are joined, a curve results as shown in Fig. 3.51. This curve is known as the 100% reference curve of the distance-amplitude curve.

If the echo from an unknown flaw crosses this curve, then the flaw is more than 5/64"; if it is below this curve, the flaw size is less than 5/64".

DGS Diagram (AVG Diagram) Method

A set of curves developed by Kraut Kramer for flaw evaluation, connecting the distance, gain and the size of known disc-like flaws, are quite useful in the comparative evaluation of discontinuities.

On the CRT screen, both defect and back-wall signals are obtained. An arbitrary reference level on a vertical scale, say 3, as shown in Fig. 3.52 is selected. The back echo height is brought to this reference level and the gain

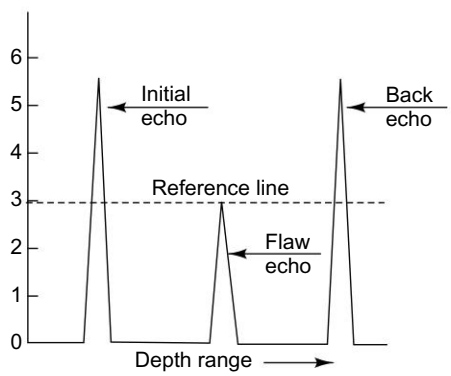


Fig. 3.52 *Flaw Assessment by DGS Method*

value is noted. Now the gain is increased until the flaw echo amplitude comes to the same reference level and this gain is noted. The difference in these two gain values gives the gain value 'G'. From the CRT oscilloscope calibration, the depth of the flaw '*a*' is known; by dividing this with the near zone 'N' for the probe, the rationalized distance of the flaw in terms of the near zone, namely 'D', is known.

This is plotted along the horizontal axis of the diagram as shown in Fig. 3.53. The point of intersection on any of the curves in this diagram, corresponding to the calculated values of 'D' and 'G', gives the rationalized flaw size 'S'. The product of the rationalized flaw size 'S' and the crystal diameter '*d*' gives the diameter of the flaw '*f*'. This diagram is applicable only when the flaw is normal to the beam axis and the flaw is assumed to be of disc type. These diagrams are drawn for materials of nominal attenuation with parallel reflective surfaces and for flat scanning.

The normalization of this diagram is done to eliminate the probe characteristics. Hence, irrespective of the probe, the diagram can be used universally.

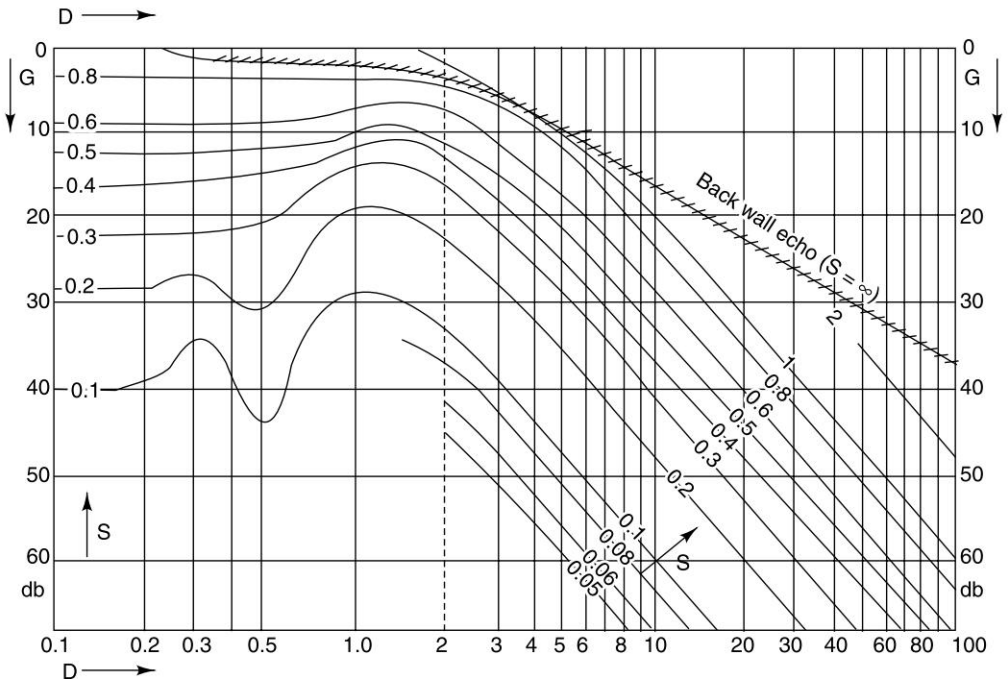


Fig. 3.53 *DGS Diagram*

Correction for Curvature and Transfer Loss

Where the surface is curved and the curvature is regular as in cylindrical objects, the testing of components with flat crystal can be done provided the convex surface has a radius of 225 mm or more. If the radius is small, either curved crystals or flat crystals with curved shoes suitably shaped can be used. In case the standard flat bottom hole calibration blocks are adopted for the curved surface, the practical approach is as follows:

A flat bottom hole block is selected, whose total height is equal to the diameter of the part under test. The probe is positioned away from the flat bottom hole to get the back echo. The gain is adjusted such

that this back echo comes to a readable height on the vertical range of the CRT screen; the gain value is noted. Now the curved part is scanned with this gain. The back echo is found to be less than the earlier height or sometimes there is no back wall echo at all, due to transmission loss at the curved entry surface. The gain is slowly increased until the back echo from the curved part attains the same height. The difference in these two gain values is due to curvature, which is what is required for compensating the transmission loss. Hence, any curved part can be tested and evaluated after drawing the distance-amplitude curve with flat reference blocks and then increasing the gain value by the compensation gain value.

Most of the engineering components do not have a surface finish comparable to that of a calibration block. Therefore, after calibration with a standard block, when the probe is transferred on to the test component, there will be some energy transmission loss on the component surface. For this transfer loss, correction can be applied. As explained earlier, a calibration block equal to the thickness of the part under test is taken and multiple echoes are obtained by placing the probe on the calibration block away from the target hole. Curve *A* is thus obtained. With the same gain setting, the part under test is scanned and multiple echoes are obtained. If the peaks are joined, Curve *B* is obtained (Fig. 3.54).

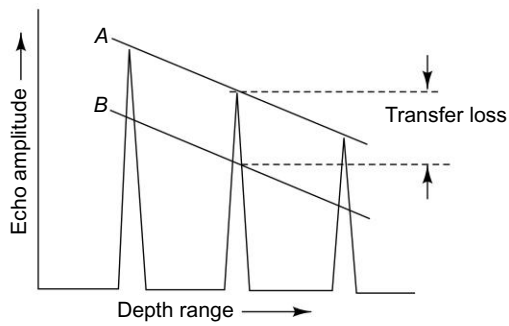


Fig. 3.54 *Transfer Loss Correction*

Though material, gain and other conditions are similar, there is a transfer loss, resulting in a drop in echo amplitude. Now the gain is slowly increased such that Curve *B* overlaps Curve *A* and the difference in gain to bring Curve *B* to Curve *A* level is noted. After plotting the distance-amplitude curve on the calibration block, the gain is increased by a value equal to the transfer loss and the component is tested at this corrected gain value. Similarly material attenuation correction can be applied and different materials tested with available blocks.

Guidelines for Acceptance/Rejection

After assessing the size of a defect, a final verdict as to acceptance or rejection is required. Guidelines for the acceptance of critical, stressed engineering components are:

(a) For forgings and other primary members that are finished or semi-finished a single echo amplitude more than or equal to the one obtained from a 2 mm (5/64") diameter flat bottom hole is not acceptable

(b) For any defect giving an amplitude indication greater than a 1.2 mm (3/64") diameter flat bottom hole is accepted and the estimated defect is recorded

(c) A stringer type of discontinuity giving a continuous indication with an amplitude greater than that given by a 1.2 mm diameter flat bottom hole over a length exceeding 12.5 mm is unacceptable.

(d) Multiple discontinuities giving indications greater than that given by a 1.2 mm diameter flat bottom hole are considered acceptable provided the minimum separation between them is 25 mm

(e) Over and above clauses (a)–(d), if a defect indication is found to break into a surface or hole on the finished part, the defect is unacceptable

Plotting of Defects

The defect in a component should be marked with a pencil and surrounded with suitable paint. The center of each defect should be marked on the scanning surface of the component as '*X*'. The size of the defect should be marked above '*X*' in mm. The depth of each defect should be marked below '*X*' in mm. A typical marking for a 1.2 mm diameter defect at a depth of 19 mm from the scanning surface is:

$$\left.\begin{matrix} 1.2 \\ \times \\ 19.0 \end{matrix}\right\}$$

Guidelines for Defect Evaluation in Heavy Engineering Applications

In heavy engineering applications involving huge components, large defects are tolerable. Comparing the echo to that of an artificial flat bottom hole is neither useful nor necessary. In such cases, the general approach to evaluate the defect is to compare the defect echo amplitude to that of the back echo and express this in percentage. A typical classification of defects for heavy forging is given in Table 3.4.

TABLE 3.4 *Guidelines for evaluation of defects in heavy engineering applications*

Component Classification	*Defect Nature and Sonic Indications*		*Extent of Defect Permissible*
	Isolated	*Distributed*	
Class I	Maximum height of both flaw echo and back echo is 100%	Not permitted	Maximum number of defects permissible over a specific length and the minimum separation distance between two permissible defects are as agreed upon between the parties concerned
Class II	Maximum height of Flaw echo: 75% Back echo: 25%	Maximum height of Flaw echo: 100% Back echo: 100%	
Class III	Maximum height of Flaw echo: 100% Back echo: 50%	Maximum height of Flaw echo: 75% Back echo: 25%	

Class I: Highly stressed dynamic components (e.g. steam turbines)
Class II: Medium stressed components (e.g. hydraulic components, die blocks, etc.)
Class III: Low stressed general engineering components (e.g. mill rollers and general engineering items)

Guidelines for Acceptance/Rejection of Welds

Welding defects are assessed by comparing the defect signal with the signal obtained from a standard reference block made of the same material as that of the job. A typical reference block is shown in Fig. 3.55.

where L = Length of the block determined by the angle of the search unit and the beam path

T = Thickness of the block depending on the job thickness

D = Depth of the side drilled hole (normally 1½")

d = Hole diameter varying from 3/32" to 3/8" depending the job thickness

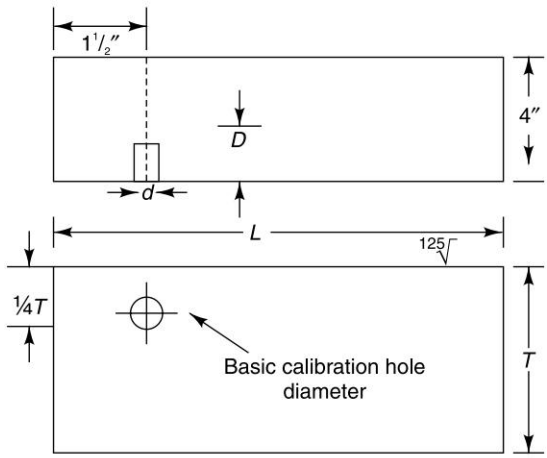


Fig. 3.55 *Calibration Block for Weld Testing*

Calibration for Angle Probes

The basic calibration hole is 3/8" diameter for any thickness greater than 1". As an alternate to the hole, a '*V*' or square notch of a known depth (usually a percentage of the thickness of the test material) can be made on the test part in a non-critical area. After the testing is over, the notch can either be weld corrected or left as it is, depending on the design requirement.

With either the hole or the notch, the distance-amplitude curve can be plotted with the angle beam probe. The search unit is positioned on the calibration block so as to beam the side-drilled hole as indicated in Fig. 3.56.

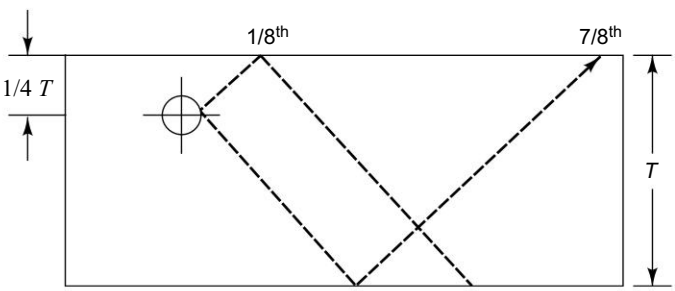


Fig. 3.56 *Angle Beaming of Side-Drilled Hole*

The search unit is moved such that the maximum response is obtained at 3/8th of the beam path position (one beam path corresponds to one skip distance probe movement) and this echo amplitude is brought to a readable height by adjusting the gain. The peak of the echo is marked on the CRT screen. Similarly, the probe is placed at 5/8th and 7/8th beam path positions to get the maximum response and the peaks are marked. The marked points are joined to form the primary reference curve. This curve is known as the 100% primary reference line and the line joining the 50% amplitude points of the echoes is known as the 50% reference line. After this, the gain setting should not be disturbed. For practical purposes, as agreed between the contracting parties, any hole diameter or notch size is defined as the limit of acceptance. Any defect giving a response more than 50% level is recorded and

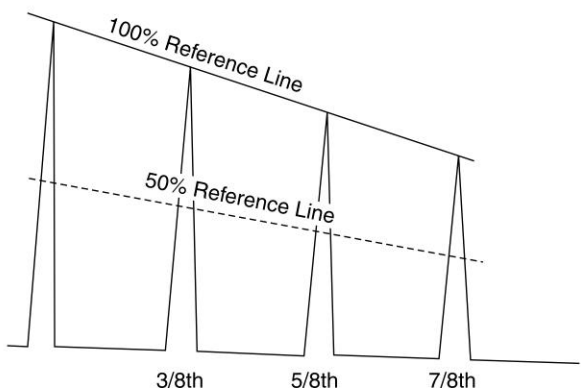


Fig. 3.57 *DAC Curve for Angle Beaming*

any indication more than 100% can be considered unacceptable. If the surface roughness of the calibration block is different from that of the test part, transfer loss correction should be applied as discussed earlier.

Straight Beam Probe

For straight beam probes, too, the distance-amplitude curve can be drawn using the side-drilled hole. The probe is placed in position *A* and the maximum echo amplitude from the side-drilled hole at 1/4*T* position is obtained. The gain is adjusted to get the echo to a readable height and the peak of this echo is marked on the CRT screen. Similarly, the echo from 3/4*T* distance from probe position *B* is obtained and the peak of this echo is marked. The curve joining these two points is the 100% reference level and the dotted line joining the 50% echo heights is known as the 50% reference level. If agreed between the contracting parties, defects crossing the 50% level are recorded and those crossing the 100% level are rejected.

A typical DAC curve for a straight beam probe is illustrated in Fig. 3.58.

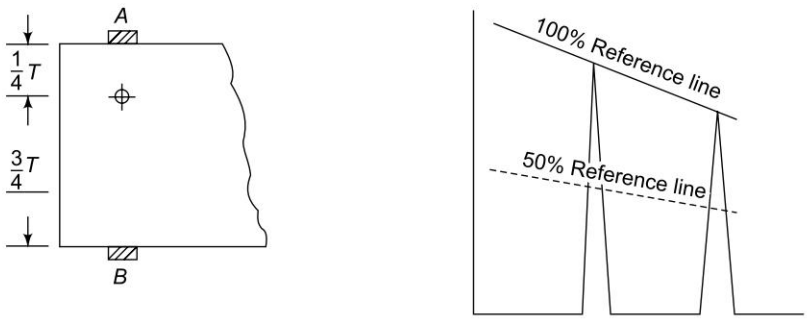


Fig. 3.58 *DAC Curve for Straight Beaming*

In both angle and normal beaming methods, defects crossing the 50% reference level are recorded. This type of recording will be useful for future evaluation regarding acceptability of critical components. This can be done by considering the distribution and the separation distance between adjacent recordable defects and the criticality of the component under test.

3.9 Effectiveness and Limitations of Ultrasonic Testing

The success of an ultrasonic test is influenced by the test location, the assembly condition, the working environment, the technicians' skills and their understanding of the geometry of wave propagation, the equipment used and the technique of test employed.

The following table gives the areas of effective ultrasonic applications during routine testing.

TABLE 3.5 *Applications of ultrasonic testing*

Product/Process	***Effective Detection***	***Limit of Detection (Approximate Linear Size)***	
Billets, forgings, extrusions, plates, sheets, bars, rods	Cracks, bursts, lamination, inclusion, voids, debond, porosity	Condition	Limit of detection (mm)
		Laboratory	1.0
		Production	2.0
Fibre-re-inforced polymer composites	Porosity, cracks, delamination fibre damage, resin rich, resin starved, impact damage, insufficient curing thickness variation	Production	2–3
Assembly	Stress corrosion, cracks, corrosion, pits, fatigue cracks, delamination, impact damage, lightning strike damage	Service	2–3

Ultrasonics has also been used successfully to bring out material inhomogeneity, phase variations and stress distribution in materials and components.

It may be noted that limit of detection can be improved appreciably with improved facility, surface condition and frequency of test.

4 Liquid Penetrant Test

4.1 Liquid Penetrant Test Basic Concepts

4.1.1 Cohesion and Adhesion

The attraction between like molecules is called cohesion, while the attraction between unlike molecules is called adhesion.

If unlike molecules are brought in contact, attraction between like molecules may be less than the attraction between unlike molecules. In this situation unlike molecules adhere to each other. As an example, if a glass plate is dipped in water, water adheres to the glass plate and wets it. This implies that whenever a solid is dipped in a liquid where adhesive forces are greater than cohesive forces, the liquid wets the solid.

The reverse happens if cohesive forces are greater than adhesive forces. This is observed when a glass plate is dipped in mercury. The two physical situations are illustrated in Fig. 4.1.

The illustrated situation shows that liquid rises above its original level when adhesion is greater than cohesion. The opposite phenomenon takes place when adhesion is less than cohesion. Now, if a glass tube with a very small bore (capillary tube) is dipped in a liquid, depending on whether adhesive forces are greater or less than cohesive forces, the liquid level will rise or fall within the capillary tube as shown in Fig. 4.2. The phenomenon of the rise or fall of the liquid level

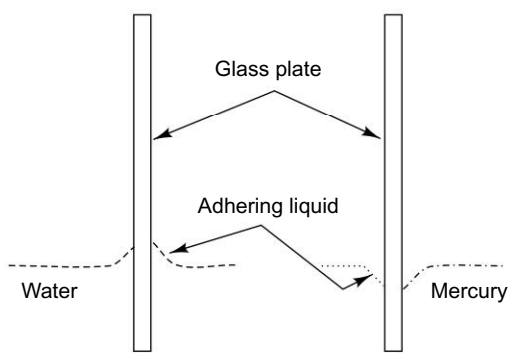


Fig. 4.1 *Effect of Cohesive and Adhesive Forces*

in a capillary tube, as a result of the relationship between cohesive and adhesive forces, is called capillarity or capillary action.

From this observation, we understand that the tendency of a liquid to penetrate or migrate into small openings such as fine fissures or cracks is due to capillary action.

Further, when a liquid wets a surface, the angle of contact or the wetting angle (defined as the angle between the contact surface and the tangent at the point of contact) is less than 90° as shown in Fig. 4.3. The wettability reduces as the contact angle increases.

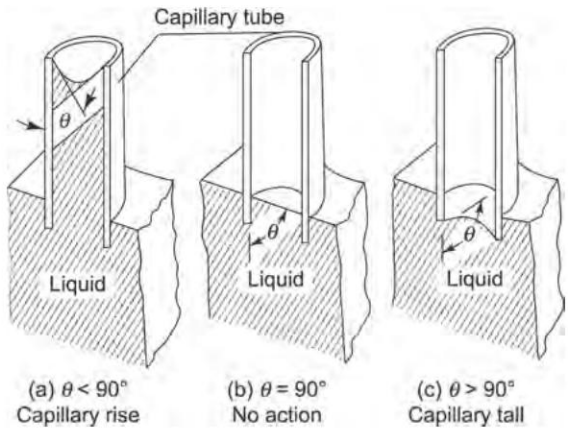


Fig. 4.2 *Capillary Action*

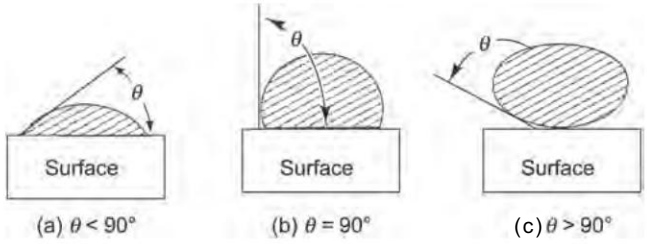


Fig. 4.3 *Contact Angle*

Table 4.1 gives the contact angles between a few contact surfaces.

TABLE 4.1 *Contact angle of some combinations of surfaces*

Materials in Contact	*Contact Angle*	*Remarks*
Glass–Water	0°	Water wets glass
Water–Paraffin	107°	Water does not wet paraffin
Glass–Mercury	140°	Mercury does not wet glass

4.1.2 Capillary Rise

Let us consider the case of the rise of liquid in a capillary tube ($\theta < 90°$) as illustrated in Fig. 4.4.

The liquid in the capillary tube rises until the downward force F due to the weight of the raised column of liquid is balanced by the vertical component of the surface tension forces. This balancing of forces results in the following relationship:

$$h = \frac{2T\cos\theta}{r\rho g}$$

or $$h = \frac{2T}{r\rho g} \text{ for } \theta = 0$$

or $$h \propto 1/r$$

where
h = Height of the liquid column
T = Surface tension force
θ = Contact angle
r = Radius of the capillary tube
ρ = Density of the liquid
g = Acceleration due to gravity

The quantity $h\rho g = 2T/r$ measures the driving capillary pressure.

In practice, a crack or a fine fissure on the surface of an engineering component is not a capillary tube of uniform cross-section, but it may be considered a capillary of variable cross-section, with a wider opening and a tapered end. The movement or migration of a liquid in the crack essentially depends on the cohesive and adhesive forces between the liquid and solid surfaces; the direction of movement depends on contact angle. If contact angle θ is less than 90°, the liquid wets the surface and moves into the crack towards the narrow end. The liquid drive pressure is given by:

Driving capillary pressure = $2T\cos\theta(1/r_1 - 1/r_2)$

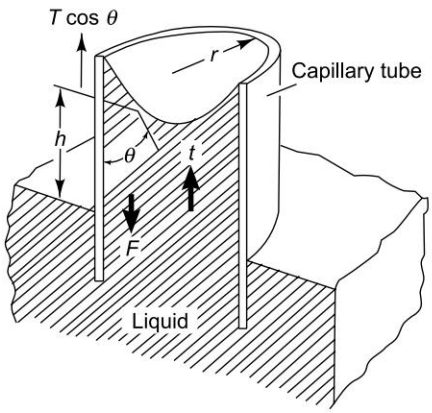


Fig. 4.4 *Capillary Rise*

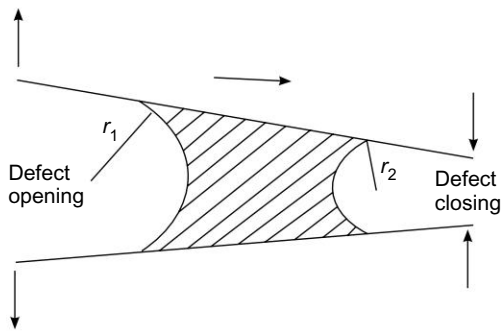


Fig. 4.5 *Capillary Flow in a Tapered Crack*

Capillary pressure has a great influence on the movement of liquid in capillaries. In solid surfaces with fine pores of varying diameters, the capillary pressure can reduce or accelerate the rate of movement of the penetrating liquid through the pores.

An approximate expression for the distance travelled by the liquid in a uniform capillary cross-section is given by:

$$L^2 = \frac{T\cos\theta.t}{2\eta}$$

where
L = Distance traveled
t = Time taken
η = Coefficient of viscosity
θ = Contact angle
T = Surface tension

This shows that a liquid with high surface tension, low contact angle and low viscosity makes a good *penetrant liquid*.

4.1.3 Effect of Surface Contamination

Contaminants, dirt and grease significantly affect the spreading of a penetrant liquid on metallic surfaces. These usually lead to a change in surface tension and contact angle and affect the wettability of the surface. Therefore, one should be extremely careful about surface cleanliness of components while subjecting them to a liquid penetrant test.

4.1.4 Liquid Penetrant Testing Principle

The liquid penetrant method is used to detect discontinuities open to the surface in solids and essentially nonporous materials. The method employs a penetrating liquid, applied over the cleaned surface of the component, which enters the discontinuities under capillary action. After adequate time (also called dwell time), the excess penetrant is removed from the surface either by a solvent or by water, depending upon the type of penetrant used. The washed surface is dried and a thin layer of developer (either fluffy talc powder or talc powder suspended in a volatile liquid) is applied uniformly over the surface. The developer acts as a blotter and draws out any liquid remaining in the discontinuity. An indication is produced over the background of the developer layer, when the discontinuities are open to the surface. Figure 4.6 illustrates the principle.

The indications are examined either in daylight, adequate artificial illumination or under black light (λ = 3650 Å), depending on the application of a colored or fluorescent penetrant liquid.

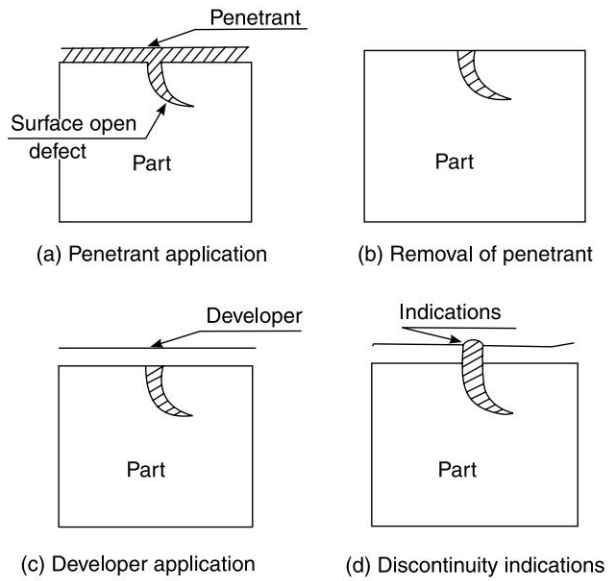


Fig. 4.6 *Liquid Penetrant Test Principle*

4.2 Liquid Penetrant System

Liquid penetrant systems are of two types, visible liquid penetrant and fluorescent penetrant. Each of these systems is further classified as water-washable, post-emulsifiable and solvent removable.

Water-washable penetrants are self-emulsifying, removed simply by washing with water. Post-emulsifiable penetrants require two-step removal. First, the excess penetrant is treated with an emulsifier for a stipulated period of time and then water washed. Post-emulsifiable penetrants do not contain a built-in emulsifier. Emulsification is accomplished by applying a separate emulsifier to make it water-washable.

Solvent removable penetrants are of the post-emulsifiable type. Instead of using an emulsifier and water wash, excess penetrant is removed by a solvent. Solvent removal is done in two stages—initially as much excess penetrant as possible is wiped from the test surface with a clean, dry, lint-free cloth. This

is followed with a second cleaning with a clean, lint-free cloth moistened with a solvent cleaner. Solvent removers are specific to a given penetrant and are recommended by penetrant suppliers.

In case of fluorescent penetrants, the removal of excess penetrant must be confirmed under black light. Incomplete removal of the penetrant may result in the formation of false indications.

The penetrant-developer combination forms the liquid penetrant system. Developers used with penetrants are categorized into four types, namely water suspended particles, water solvable particles, dry particles and non-aqueous wet particles. The first two types are generally used with water-washable penetrants or post-emulsifiable penetrants. These are applied while the test component is still wet from a water wash. Water-based developers are used on very smooth surfaces where a large number of small, irregular shaped components are involved. Dry and non- aqueous developers are used when the component is thoroughly dried after water rinsing. The drying is usually done in a hot air circulating oven. Drying time is very critical. The dry developer as a fine-grained, fluffy powder is applied using low air pressure, by a spray can or by dipping. Dry developer is applied on rough surfaces and also on sharp fillets, holes and threaded components, where wet developers tend to accumulate powder lumps.

Non-aqueous wet developer is most sensitive of all the developers. It is applied to dry test surface. Here, the powder particles are held in suspension in a rapid drying solvent, like methylated spirit. This type of developer is used for spot checks or 'in situ' test in field.

4.3 Test Procedure

The liquid penetrant test process essentially consists of the following steps:

- Pre-cleaning the component surface
- Applying penetrant liquid by dipping, spraying or brushing to form a film over the part surface and allowing it sufficient time to enter the open defect
- Removing excess penetrant with a water wash, solvent or emulsifier, and drying
- Applying a thin layer of developer, wet or dry
- Examining the component surface after the developing time under adequate lighting
- Post-process cleaning and surface protection

Figure 4.7 gives the process flow chart.

4.3.1 Surface Preparation

Test surface contaminated with dirt, grease, oil, rust, welding flux, acid, etc. should be thoroughly cleaned and paints and metallic coatings should be removed before applying the penetrant liquid.

Depending on the surface contamination, one of these methods can be used for surface preparation: mechanical cleaning, solvent cleaning, vapor degreasing, detergent cleaning, steam and ultrasonic cleaning.

Mechanical cleaning Mechanical methods of cleaning such as wire brushing abrasive blasting and metal scraping are used. Then, chemical etching is carried out to reopen any discontinuity that might have been closed during cleaning. After cleaning, the component is fully dried before proceeding to the next step.

Solvent cleaning Solvents like naptha, mineral spirit, acetone, iso-propyl alcohol or mythelene chloride are used to flush away the oil and grease. These solvents do not remove rust, scale, welding flux or

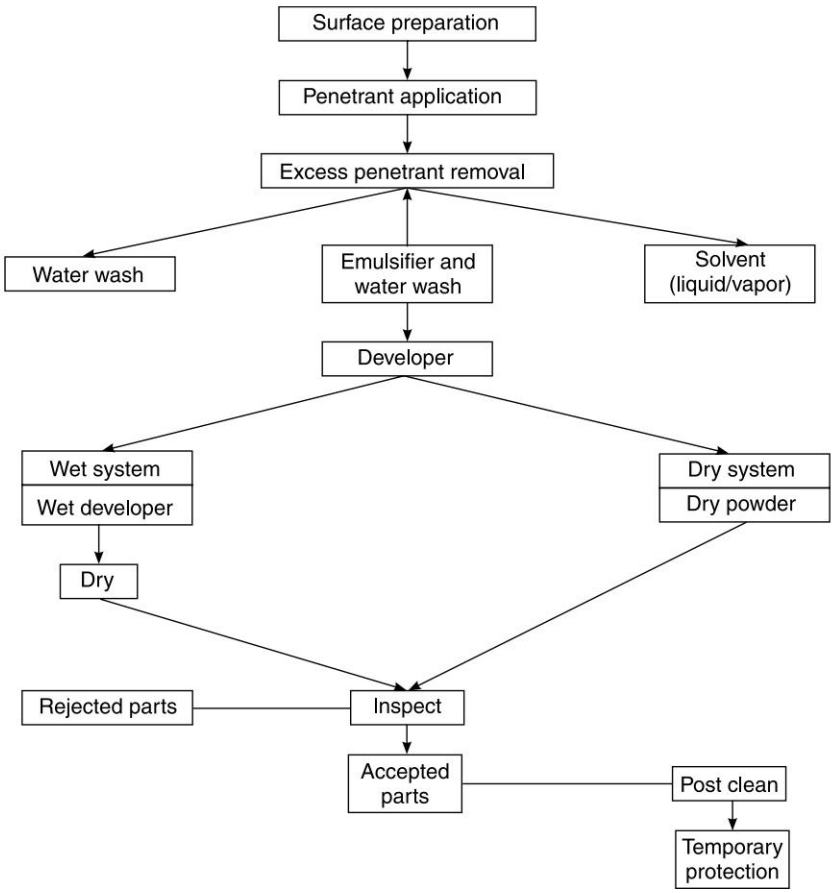


Fig. 4.7 *Liquid Penetrant Process Flow Chart*

inorganic soils. Most of the solvent cleaners are toxic and flammable; so, one must be careful while using them. Breathing the fumes, skin contact, open flames or smoking should be avoided while using the solvents.

Vapour degreasing This is used to remove organic contaminants like oil and grease. Not only the surface is cleaned this way but any moisture entrapped in discontinuities also evaporates. However, if chlorinated solvent is used, it can be harmful to materials like nickel, titanium, stainless steel, etc.—this method is not used for cleaning parts made of such materials.

Detergent cleaning Non-inflammable, water-soluble compounds mixed with water are used for removing oils. Detergent solutions can be acidic or alkaline. After cleaning the surface, the component is thoroughly rinsed and dried using hot air blowers, heat lamps or ovens.

Steam cleaning This method is useful for cleaning large, unwieldy items. It removes inorganic oils as well as many organic contaminants. However, deep discontinuities may not be effectively cleaned. Therefore, a follow-up solvent soak is often useful.

Ultrasonic cleaning This method is often combined with a solvent or detergent bath to improve cleaning efficiency. After cleaning, the test components are heated to evaporate cleaning fluids.

Acid cleaning Strong acid solutions are employed to remove heavy scaling. Mild acid solutions are used for light scaling. Weak etching solutions are also used for removing lightly smeared metals.

Some precautions are essential after acid etching. The part should be baked at an appropriate temperature for a sufficient time, soon after etching, to avoid hydrogen embrittlement.

Halogenated solvents should not be used for titanium and titanium alloys, which are prone to cracking as a result of contact with halogenated compounds (halides less than 25 ppm and sulphur less than 1% by weight of residue is needed).

4.3.2 Application of Liquid Penetrants

Liquid penetrants can be applied by dipping, spraying, brushing or flowing. In the dipping method, the component is generally lowered into a tank containing the penetrant liquid. It is then raised and allowed to drain. The spraying method involves the use of conventional spray guns or pressurized spray cans. Brushing is done with brushes or swabs. Flowing requires pouring the penetrant over the test specimen and allowing it to drain. Regardless of which method is used, the area to be tested must be adequately covered by the penetrant liquid.

There is a minimum penetration time for the penetrant liquid, which must be allowed after applying it. The guidelines for penetration time recommended by various manufacturers, for controlling specification and standards, is given in Table 4.2.

TABLE 4.2 *Guidelines on penetration time*

Material	*Form*	*Type of Defects*	*Minimum Penetration Time (minutes)*
Aluminum and magnesium alloys	Castings, forging, welds, all forms	Porosity, cold shut, laps, fatigue cracks, porosity	15 30
Stainless steel	Castings, forging, welds, all forms	Porosity, cold stunt, laps, fatigue cracks, porosity	30 60
Brass and bronze	Castings, forging, brazed parts, all forms	Porosity, cold stunt, laps, fatigue cracks, porosity	10 15–30
Plastics	All forms	Cracks	5–30
Glass	All forms	Cracks	5–30
Carbide-tipped tools	Lack of bond, porosity, grinding crack		10

While the table gives guidelines for the penetration time, the correct time is determined by trials. Also, the penetrant liquid must remain wet throughout the penetration time.

4.3.3 Removal of Excess Penetrant

Three methods are used for removing excess penetrant from the surface of the component: water washing, post-emulsifying and solvent removing.

The water wash method employs self-emulsifying penetrants. Here, the excess penetrant is removed by simply washing with water. The post-emulsifier process involves a two-step removal. First, the excess penetrant is treated with an emulsifier for stipulated periods of time as recommended by the manufacturer and then water washed. Solvent removal is done in two stages. Initially, as much penetrant as possible is wiped from the test surface with a clean, dry, lint-free cloth. This is followed by a second cleaning with a clean, lint-free cloth moistened with a solvent cleaner. Solvent removers recommended by the penetrant supplier are used. It is not advisable to flush the surface with solvent.

In the post-emulsifier method, the penetrant does not contain a built-in emulsifier. Emulsification is accomplished by applying a separate emulsifier to make the penetrant water-washable. Emulsifiers are applied by dipping, flowing or spraying. The emulsifier is allowed to remain on the surface until it has mixed with the excess penetrant on the surface, but not long enough to mix with the penetrant in the discontinuity. Emulsifying time is critical.

4.3.4 Developer Application

A developer is applied to get the penetrant in the discontinuities back to the surface so that it can form an indication of the discontinuity. The penetrant is drawn out by capillary action in the reverse direction. The developer tends to enhance or make discontinuities appear larger than the actual size. There are four types of developers:

- Water suspended particles
- Water soluble particles
- Dry particles
- Non-aqueous wet particles

Two types of developers are used with water-washable or post-emulsifiable penetrants. These are applied while the test component is still wet from the water wash. Water-based developers are used on smooth surfaces where a large number of small irregularly shaped components are involved.

A dry or non-aqueous developer is used on components that are thoroughly dried after water rinsing. The drying is usually done in a hot air circulating oven. Drying time is critical to avoid poor sensitivity.

A dry developer is used on rough surfaces and gives better results than a wet developer. It is also used on sharp fillets, holes and threaded components, where a wet developer tends to accumulate the powder in a lump. The non-aqueous wet developer is the most sensitive of all developers. It is applied only to dry test surfaces. Here, the powder particles are held in suspension in a rapidly drying solvent like methylated spirit. This developer is ideally suited for ‘in situ’ work in the field.

4.3.5 Examination, Interpretation and Evaluation

Penetrant indications are examined under natural daylight or under artificial illumination of at least 500 LUX, where visible colored penetrants are used. In case of fluorescent penetrants, examination is carried out in a dark enclosure under black light (ultraviolet light) of minimum 70-LUX intensity. A minimum of 5 minutes is allowed for the black light to warm up and for the examiner’s eye to get adapted to the dark.

The identification of indications requires practice. For example, cracks, cold shunt, seams and forging laps, all show up as continuous line indications. If these discontinuities are tight, they appear as an intermittent or broken line. Small dots and rounded indications generally indicate porosity or blowholes.

The size of the indication and the intensity and degree of bleeding can sometimes give a rough estimate of the depth of the discontinuity; fine cracks show a faint indication. Figure 4.8 shows some penetrant indications and Table 4.3 gives the indications of some defects.

TABLE 4.3 *Indications of some defects*

Nature of Defect	*Visible Penetrant*	*Fluorescent Penetrant*
Cracks	Thin red lines—depth indicated by the degree of spread	Thin, greenish-yellow lines
Very tight crack	Series of very small red dots in continuous formation	Series of very small, greenish-yellow dots
Porosity	Series of red spots spread over the surface	Series of greenish-yellow spots
Shrinkage/micro-shrinkage	Pale red blotches	Pale greenish-yellow blotches

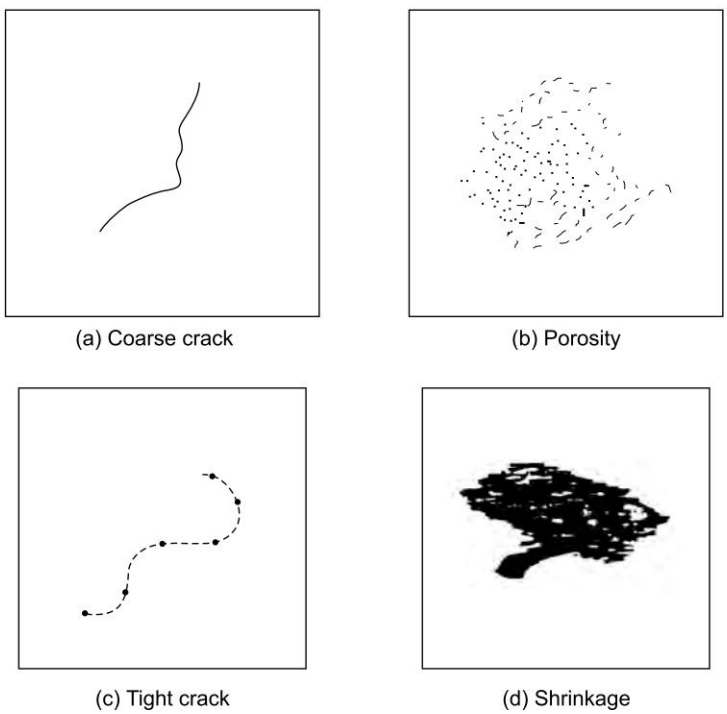


Fig. 4.8 *Typical Penetrant Indications*

Sometimes, false indications create difficulty in interpretation. These indications are due to:

- Improper washing due to surface roughness
- Penetrant seepage and smearing due to press fit multi-layer components
- Geometrical constraints in case of fillets, threaded roots and key ways

One should be extremely careful in evaluating such indications. The observed discontinuities are evaluated for specific end applications. The discontinuities are evaluated in a component considering the following:

- Design and contractual requirements
- Nature, extent and distribution of defects
- Whether subsequent operation will result in the removal of the observed defect

Broadly speaking, the observed defects are classified into two groups:

1. **Gross and propagative surface defects** like cracks, tears, cold-shuts, shrinkages, seams and laps. These defects are not acceptable in critical components, which are subjected to high temperature, dynamic loading, high impact and fatigue loading.
2. **Non-propagative surface defects** like gas porosity, micro-shrinkage and sponginess are acceptable to some extent as they do not affect mechanical properties significantly, within certain limits. Nonferrous cast surfaces invariably exhibit these defects. The evaluation of such components is not done on penetrant indication alone. Depending on the criticality of component application radiographic examination is also carried out for its proper evaluation.

To determine the criteria of acceptance of these defects one has to consider the size, distribution and distance of separation between two acceptable, individual/group of defects, which still ensure design-stipulated properties. In fact, it is essential to generate necessary data for evaluating a component for a specific property requirement.

4.3.6 Post-process Cleaning

The final step in the liquid penetrant process is post cleaning after the examination. Post cleaning is necessary to avoid corrosion and to facilitate further processing of the test component. Developers are generally removed by water washing. In general, the cleaning methods employed in post cleaning are the same as those applied for pre-cleaning. Further, parts that have already undergone the visible penetrant test should not normally be subjected to a fluorescent penetrant test.

4.3.7 Safety Precautions

The following safety precautions are essential while performing a liquid penetrant test:

- Adequate ventilation must be made available while handling cleaners, penetrants, emulsifiers or developers
- Gloves must be worn during the test. Remains of fluorescent penetrants on skin, clothes and gloves must be checked in black light after the test and washed properly
- The manufacture's instructions should be followed while using a black light source. Sodium glass spectacles are worn while examining the components
- Pressurized spray cans should be stored in a cool, dry area, protected from direct sunlight. Open flames should be avoided. Any temperature above 50°C may cause the pressurized to burst.

- The draining of chemicals in the drainage system, surface water or dumps should be approved by health authorities

4.4 Effectiveness and Limitations of Liquid Penetrant Testing

The liquid penetrant test is used extensively for locating and evaluating discontinuities open to the surface in all non-porous materials during the production, processing and maintenance of engineering components and assemblies. A variety of industries like nuclear, aerospace, shipping, railways, chemical, petroleum, food, paper, etc. use the liquid penetrant test for economy, safety and ease of interpretation. However, the success of the test methods depends on the careful operation of the procedures. Areas of effective application of this test method during routine testing are given in Table 4.4.

TABLE 4.4 *Applications of the liquid penetrant test*

Product/Process	***Effective Detection***	***Limit of Detection (mm)***	
All non-porous, ferrous and non-ferrous materials like castings, weldments, forgings, assemblies and structures, machined, anodized, corroded, finished product, etc.	Open surface defects like cracks, porosity, folds, laps, seams, corrosion and grinding cracks	Laboratory level	0.25
		Production level	1.0
		Service level	Fatigue cracks 1.0

5 Magnetic Particle Test

5.1 Magnetic Materials

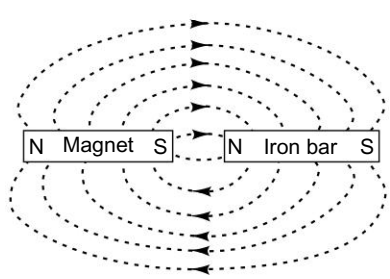
Materials are classified as ferromagnetic, paramagnetic or diamagnetic depending on their behavior in a magnetic field. Ferromagnetic materials are easily magnetized and show a high value of magnetic susceptibility. Also, it is observed that the magnetization of such materials is not proportional to the magnetizing field. This results in considerable variation in magnetic susceptibility magnetic permeability in the magnetizing field.

Paramagnetic materials have magnetic permeability greater than one and of a small positive value magnetic susceptibility.

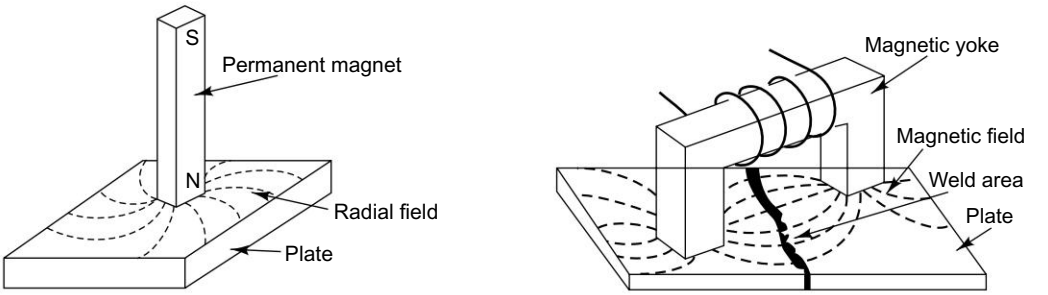
Diamagnetic materials have magnetic permeability less than one and constant magnetic susceptibility.

5.2 Magnetization of Materials

Materials are magnetized by a permanent magnet or by the magnetic field produced by an electric current. The earth's magnetic field also magnetizes materials. Here, we are concerned with magnetization by a permanent magnet or by a magnetic field produced by an electric current. Figure 5.1 illustrates magnetization by permanent magnets.



(a) Magnetization of an iron bar by a permanent bar magnet



(b) Production of a radial field by a permanent bar magnet (c) Production of a magnetic field by a permanent magnet yoke

Fig. 5.1 *Magnetization by Permanent Magnets*

5.2.1 Magnetic Field Using an Electric Current

Direct as well as alternating currents are used to magnetize components for the magnetic particle test. The choice of current depends on the strength, direction and distribution of the desired magnetic field. A magnetic field produced by direct current (DC) penetrates the cross-section of a component, whereas the field produced by an alternating current (AC) is largely confined to the surface of the component due to the skin effect. The direct current obtained from a rectified AC is invariably used for the magnetic particle test. Rectification of a single-phase AC gives a Half Wave Rectified Current (HWDC). A full wave rectified DC is obtained by rectifying the alternating current such that even in the reverse half of the cycle, the current is allowed to flow into the circuit in the same direction. Figure 5.2 shows the form of current thus obtained.

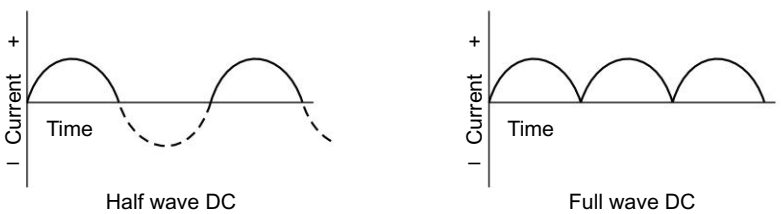


Fig. 5.2 *Forms of Half and Full Wave DC*

DC ranging from 50–6000 amperes is used in the magnetic particle test.

5.2.2 Surge Method

If a surge of high current is passed through a ferromagnetic material for a short duration and the current is then reduced to its steady lower value, the component is magnetized to its saturation value. It is not possible to attain this high state of magnetization with a lower steady current.

5.2.3 Induction Method

This method is used to magnetize ring-shaped components. Here, AC or DC is passed through the primary winding of a transformer, where the ring-shaped component forms a single turn secondary as shown in Fig. 5.3. The magnetic field is produced because of induced current in the part. This type of magnetization helps in the detection of circumferential defects. Materials of high retentivity are subjected to DC current magnetization, while those with low retentivity are subjected to AC or HWDC magnetization. The induction method of magnetization has the advantage that there is no chance of damaging the component surface due to arcing.

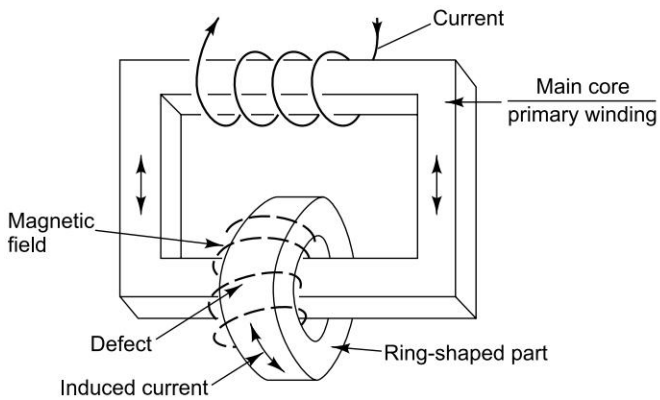


Fig. 5.3 *Magnetization of Ring-Shaped Components*

5.2.4 Solenoid Coil Method

Solenoids carrying current produce a magnetic field along the axis of the solenoid as shown in Fig. 5.4.

When a part is placed inside a solenoid coil, a magnetic field is created parallel to the solenoid axis. The field strength inside the solenoid is proportional to the product of current (Amps) and the number of turns of the coil. The strength can be varied either by varying the current or the number of turns. Solenoid-carrying currents are preferred for creating the longitudinal fields in ferromagnetic parts. For large parts, cable wire is wound directly around the part. For small parts, coils wound on movable frames are often used.

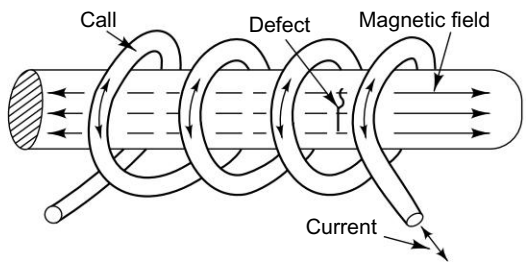


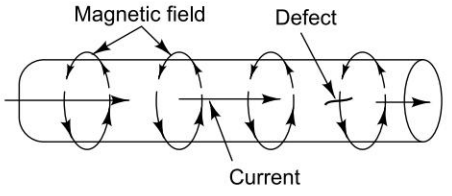
Fig. 5.4 *Magnetization with a Solenoid Coil*

5.2.5 Alternating Current Method

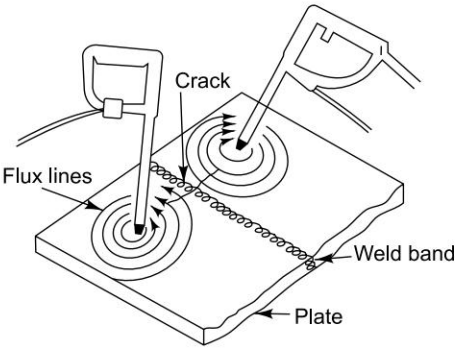
A 50-60-cycle frequency AC from commercial power lines is directly used for magnetization in this method. Only single phase is used and voltage is stepped up by using suitable transformers. At a low voltage, magnetizing current up to several thousand amperes is used. When using AC, the skin effect is used to advantage for detection of surface discontinuities.

Depending upon the requirements of magnetization, size and shape of the components, the following arrangements are employed:

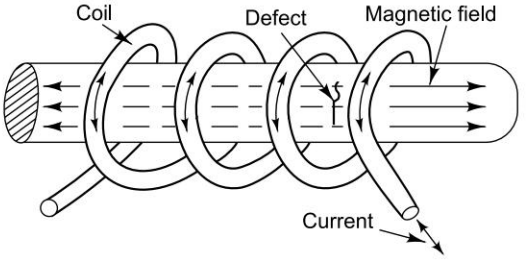
- Circular magnetization
- Longitudinal magnetization
- Coil magnetization
- Prod magnetization
- Yoke magnetization



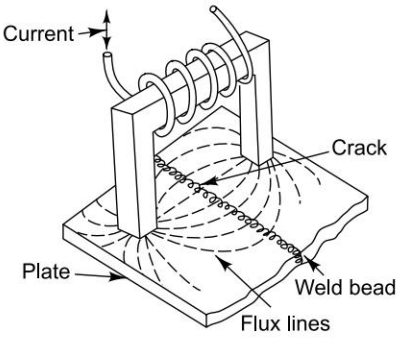
Circular magnetization



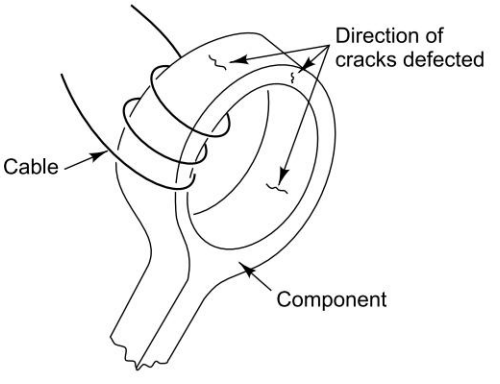
Circular magnetization using contact prods



Longitudinal magnetization



Yoke magnetization



Longitudinal magnetization using wandering cable

Fig. 5.5 *Various Arrangements of Magnetization*

5.3 Demagnetization of Materials

After completion of a magnetic particle test, it is essential to demagnetize the component, as a certain amount of magnetism is retained, depending on the:

- Magnetic characteristics of the material
- Geometry of the component
- Direction of magnetization
- Strength of the magnetic field

The reasons for demagnetization are:

- Residual magnetism may interfere with subsequent machining, causing machined chips of the material to adhere to the surface of the component or the tool
- During welding with an electric arc, residual magnetism may cause deflection of the arc and obstruct proper welding
- The functioning of navigational instruments, which are sensitive to magnetic field, is affected by the proximity of ferromagnetic components having residual magnetism
- Residual magnetism may interfere with the functioning of dynamic components if any chips are held on it like ball bearing-races, gear assemblies, etc. It also affects finishing operations like painting and plating

However, demagnetization may not be necessary under these conditions:

- If the material of the component has low retentivity
- Welded structural components, large castings, boilers, etc. made of high-strength alloys. Residual magnetism does not affect the service performance of such components
- Components that undergo heat-treatment above Curie temperature
- Components that are held in a magnetic chuck during a subsequent operation or components requiring re-magnetization in different directions

Methods of demagnetization

Table 5.1 gives the various methods used for demagnetization.

TABLE 5.1 *Methods of demagnetization*

Component	*Method of Demagnetization*
Large components of high hardness	AC coil method
Small components of medium hardness	(i) AC through current (decreasing in amplitude in stages)
	(ii) DC through current (decreasing in stages as well as alternating in direction
Localized demagnetization (big or small parts)	(i) AC yoke (ii) Reversing DC yoke

5.4 Principle of Magnetic Particle Test

When a homogeneous ferromagnetic material is placed in a magnetic field, it gets magnetized and the magnetic field forms a continuous circuit from pole to pole through the material. If any surface or subsurface discontinuity is present, the magnetic field (and the associated magnetic lines of force) gets deflected and forms a leakage field as shown in Fig. 5.6.

If fine particles of magnetic material are applied on the surface of the test material, the leakage field attracts the particles which form an outline of discontinuity and indicate the location, size, shape and extent of the discontinuity. The method is very sensitive for locating fine surface and sub-surface defects.

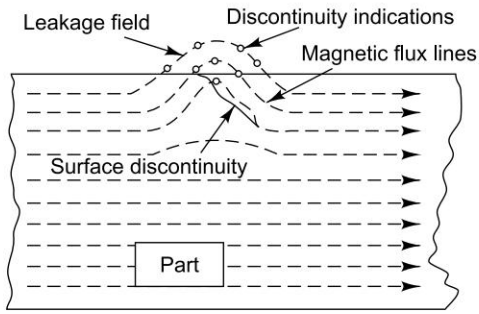


Fig. 5.6 *Principle of Magnetic Particle Test*

The methods involved in the magnetic particle test are:

- Cleaning/degreasing of the surface and demagnetizing
- Magnetization of the component
- Application of fine magnetic particles on the surface of the component
- Examination of the component surface for defects
- Demagnetization and temporary protection

Figure 5.7 shows the process flow chart.

The following factors influence the indication of discontinuities:

- The initial state of magnetization of the component
- The direction and strength of the magnetizing field with respect to size, shape and orientation of the discontinuity
- The magnetic nature and chemical composition of the component material
- The size, shape, geometry and surface finish of the component
- The physical characteristics of the magnetic particle (e.g. size, shape)

The magnetic particle test methods are grouped as:

- **Dry method:** In this method, finely divided ferromagnetic particles, in dry powder form, are uniformly dusted over the magnetized surface, either by an atomizer or a spray grain. The powder is gray, black or red to provide suitable contrast indication. The method is used to examine rough surfaces and is also convenient for fieldwork.
- **Wet method:** In this method, fine magnetic particles suspended in kerosene or any liquid vehicle are sprayed over the test surface after magnetization. Magnetic particles used here are fine compared to those used for the dry method. The size of the particles is maintained in the range of 10–50 microns which makes this method sensitive to the detection of fine defects.
- **Fluorescent method:** In this method, magnetic particles are coated with a fluorescent dye and used where the surface finish is fine. The components are examined under ultraviolet light ($\lambda = 3650$ Å). The method is particularly useful in locating discontinuities in corners, key ways, deep holes etc.

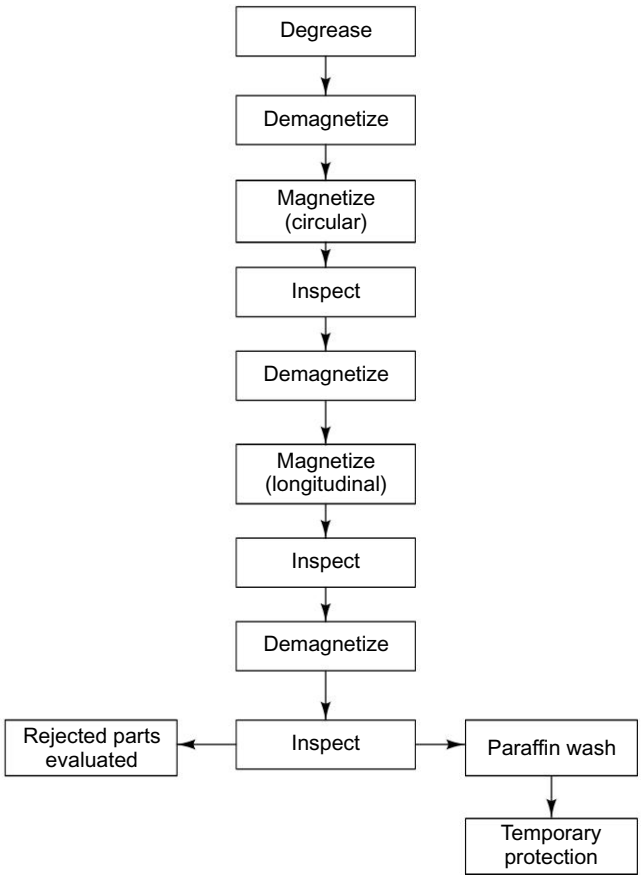


Fig. 5.7 *Magnetic Particle Test Flow Chart*

- **Residual method:** In this method, the magnetizing field is withdrawn after magnetizing the component. Magnetic particles are applied on the surface of the component after the field is withdrawn. The method is applicable for components that show high retentivity. It is essential that residual magnetism be strong enough to produce a leakage field at discontinuities.
- **Continuous method:** In this method, a magnetic powder is applied on the component surface when the magnetic field is still on. To produce a meaningful indication during the test, the level of magnetization must be sufficient to produce a strong leakage field to attract and hold fine magnetic particles.

In the usual current flow method of magnetization, the magnetizing current is measured by an ammeter, which reads the root mean square (rms) or average value of current and not the peak current. It is the peak current that determines maximum magnetization. This value is higher than what is indicated by the ammeter reading. Figure 5.8 gives the peak value of current for various wave forms.

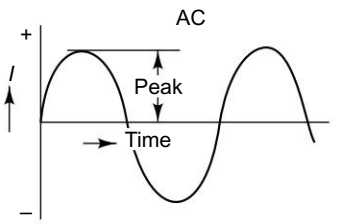
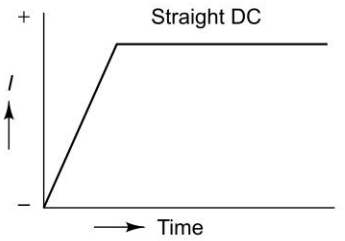
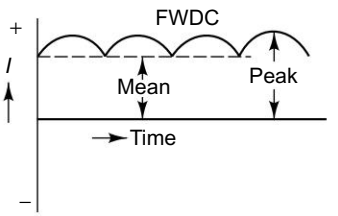
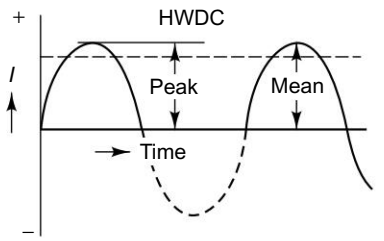
Wave Form	*Ammeter Reading*	*Relationship*
	I_{rms}	$I_p = \sqrt{2} \cdot I_{rms}$
	I_{av}	$I_p = \frac{\pi}{2} \cdot I_{av}$
	I_{mean}	$I_{peak} = I_{mean}$
	I_{mean}	$I_{peak} = \frac{\pi}{2} \cdot I_{mean}$
	I_{mean}	$I_{peak} = \pi . I_{mean}$

Fig. 5.8 *Relationship between rms and Peak Values of Current*

In practice, one comes across components of varying geometrical shapes and cross-sections. This demands some compromise, simplification and approximation in the selection of the most effective method of magnetization. Complicated shapes are considered to be made up of several simple geometrical shapes joined together. The approximate current is applied to each section separately to bring out the longitudinal or transverse defects. Table 5.2 gives the guidelines for selection of current.

TABLE 5.2 *Guidelines for the selection of current*

Component Shape	*DC*	*AC*	*FWDC*	*HWDC*
Current for round components (Amp/mm of diameter)	28	20	18	9
Current for irregular-shaped components (Amp/mm of perimeter)	9	6.4	5.7	2.9

In many cases flexible cables are used, particularly for the examination of bore or lug areas of complex and large components, as shown in Fig. 5.9.

Using flexible cables as coils around large ring-shaped components, successive areas are examined. The optimum magnetizing current is estimated by the relation:

Peak current = 16 R/N, where R = Radius of the ring (mm)
N = Number of turns of coil

In the coil magnetizing technique, the component is placed inside a current-carrying coil and magnetized in a direction parallel to the axis of the coil as shown in Fig. 5.10.

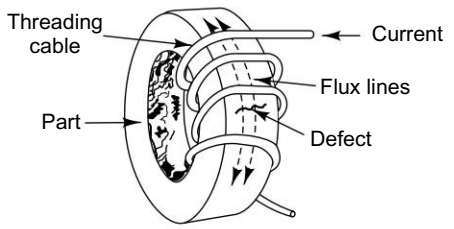


Fig. 5.9 *Flexible Cable Threading Magnetization*

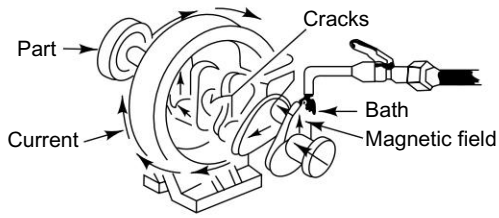


Fig. 5.10 *Coil Magnetization*

Discontinuities transverse to the axis of the coil are detected. The sensitivity of the flaw detection depends on:

- The shape and size of the specimen and coil
- The ampere turns of the coil

The magnetizing current is adjusted such that the magnetizing field is just below saturation value. The state of magnetic saturation is observed by observing the furring of magnetic particles on the surface of the component. For a helical coil of magnetization, the following relation is used for computing magnetizing current:

$$NI = \frac{C}{L/D}$$

where I = Current in amperes
N = Number of turns in the coil
L/D = Component length to diameter ratio
C = Constant depending on the type of magnetizing current

The various values of this constant are given below:

Value of Constant 'C'	*Magnetizing Current*
32,000	DC
22,000	AC & FWDC
11,000	HWDC

Where L/D ratio is greater than 15, a value of current corresponding to $L/D = 15$ is used.

This relationship is valid when the cross-sectional area of the test part is 10% or less of the cross-sectional area of the coil.

Long components are magnetized by moving the coil along the length of the components, giving as many number of coil shots as the length of the component warrants. Whenever the prod type of magnetization is used, the optimum magnetizing current is selected according to guidelines given in Table 5.3.

TABLE 5.3 *Guidelines for Current Selection for Prod Magnetization*

Prod Spacing in mm	*Current in Amperes*	
	Section Thickness < 20 mm	*Section Thickness 20 mm and above*
50–100	200–300	300–400
101–150	300–400	400–600
151–200	400–600	600–800

Generally, 9 amperes/mm prod spacing is considered satisfactory.

Permanent magnets are also used to magnetize components, particularly for field applications.

During the application of these techniques, it is useful to remember the following points:

- The magnetizing field should be at right angles to the direction of expected discontinuities as far as possible
- The presence of a non-magnetic surface finish like paint or plating reduces the flaw detection sensitivity. Therefore, the magnetic particle test is carried out prior to the application or after the removal of such coatings, if the coating thickness exceeds 0.025 mm. If the coating thickness is less than 0.025 mm, the test is carried out without removing the coating. The coating should be removed only at contact points in case of the DC magnetization method
- Although guidelines for current selection for various methods of magnetization are given, it is essential to prepare a specific technique for each component, giving the precise value of the current and illustrating the various directions of magnetization

5.5 Magnetic Particle Test Equipment

The magnetic particle test equipment essentially consists of:

- A means to magnetize the component
- A device for the application of magnetic particles
- A means of demagnetizing the component after the test

Depending on the requirement, the equipment could be portable or stationary.

Portable equipment like permanent magnet yokes, prods and cables are useful for fieldwork, where an electrical power source is not available or in areas of explosive hazards.

In a stationary system, the components of the equipment are mounted on a table. It consists of a transformer working at low voltage between 6–27 volts and giving a current in the range of 2,000–20,000 amperes.

To facilitate demagnetization, current reversing switches are provided in the equipment. A hose with a lever-operated nozzle is provided for the application of the magnetic particles suspended in carrier fluid. The carrier fluid is agitated manually or by a pump to prevent the particles settling.

For large and heavy components, stationary equipment may not be suitable, so a heavy duty DC, multidirectional magnetization system is used. In this system, two or more fields are created in quick succession. This enables the detection of defects oriented in different directions.

5.6 Magnetic Particle Test Procedure

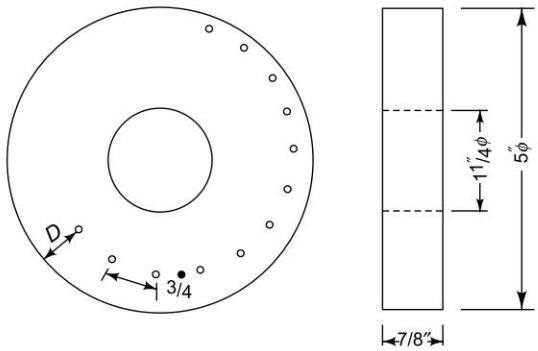
The objective of the magnetic particle test is to ensure that all surface and sub-surface discontinuities such as cracks, inclusions, pores, shrinkages, laps, folds, seams, etc. arising out of manufacturing operations and service constraints, are detected for the evaluation of components. For this, it is necessary that certain surface preparations be carried out before subjecting the components to magnetization and further operations. A process flow chart is given in Fig. 5.7. The first step in the magnetic particle test is to clean the surface. Components with rough and scaled surfaces are pickled in a mixture of 10% H_2SO_4 and 5% HF or 10% HCl and 2-gm/liter-Stanic solution to loosen or remove adherent surface scales, and thoroughly washed in cold water. Components are subjected to shot blasting until all scales are removed. This is followed by degreasing to remove any oil, grease, dirt, corrosion residue or marking dyes. Machined components are not subjected to pickling and shot blasting.

Next, it is often advantageous, though not mandatory to demagnetize the component to relieve it of any residual magnetism and then magnetized according to a pre-established technique.

The component is examined under proper lighting conditions. Indications are interpreted and evaluated in terms of pre-established standards of acceptance. The accepted components are finally cleaned, demagnetized and given a surface protection.

5.7 Standardization and Calibration

The purpose of the standardization of the magnetic particle test system is to ensure that the equipment and accessories are working under conditions of acceptable and reproducible sensitivity. To ensure this, the system is calibrated for detecting the smallest discontinuity with a high degree of confidence. In practice, artificial discontinuities are made in a test piece and variables of the test system are optimized to indicate these discontinuities clearly under practical conditions of observation. Magnetic particle test systems employ standard test blocks containing artificial discontinuities. The block is made of tool steel and is ring-shaped. It contains 12 holes of the same diameter, located at different depths as shown in Fig. 5.11.



Hetz →	1	2	3	4	5	6	7	8	9	10	11	12
Diameter (inch)	← 0.070″ Common in all →											
D (inch)	0.070	0.140	0.210	0.280	0.350	0.420	0.490	0.560	0.630	0.700	0.770	0.840

Fig. 5.11 *Calibration Block*

Before starting each shift of work, the test block is degreased, demagnetized and magnetic checks are carried out. The maximum magnetizing current that gives a satisfactory indication at each hole is established and recorded for the specific magnetic unit. These values are utilized to establish the satisfactory functioning of the test system at periodic intervals. Failure to obtain a satisfactory indication during periodic checks signifies one or all of the following:

- There is a concentration of magnetic particles below the optimum level
- The ammeter reading is inaccurate
- Some other malfunctioning of the equipment

5.8 Interpretation and Evaluation

After magnetization and the application of magnetic particles, the surface of the component is examined. In case non-fluorescent particles are used, the examination is carried out under daylight with the help of a magnifying glass at an illumination of 500 lux. If artificial light is used, this illumination can be achieved by a 80 W fluorescent tube or a tungsten filament lamp of 100 W.

The fluorescent method makes use of dyes that glow when exposed to black light.

While examining the component one has to be careful in distinguishing flaw indications from false indications.

Some of the defects and their observed indications are discussed next.

1. *Nonmetallic inclusions*: Insufficient cleaning of the metal during or after melting gives rise to this defect. These defects may or may not show a sharp indication, depending on their severity. Generally, these defects show up as stringers running along the axis of the product or along the fibers in the forging.
2. *Seams*: These defects are observed in rolled products and are formed during rolling due to the presence of laps, surface tears or scales. These defects are generally elongated. A single, deep seam shows a sharp indication but clusters of tiny seams may give misleading a indication.

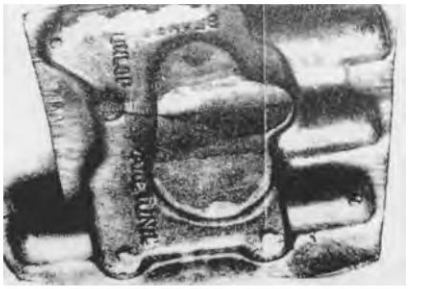
3. *Cooling cracks*: This defect occurs in steel with high hardenability, such as tool steel. Cracks are deep and give a strong indication along the grain fibers.
4. *Laminations*: These are usually found in plates and are due to the separation of layers, due to the presence of non-metallic film. These defects are parallel to the surface and indications occur only at the sides and cut portions of the plate.
5. *Piping*: These are internal defects and the magnetic particle test does not usually reveal them unless the defects are present at the end of the part. Indications at the end of the part represent a cross-section of the piping.
6. *Forging laps*: These are folds of metal squeezed together during forging. They have irregular contours and occur at right angles to the direction of metal flow. The indications of forging laps are not well defined due to a weak leakage field.
7. *Flash line cracks*: These are associated with and run along the flash line of the forging. They are deep and give strong indications.
8. *Forging bursts*: These are ruptures that occur when forging is carried out at a temperature that is too cold or too hot. Bursts may be on the surface or internal. They consist of numerous small and large cracks all over the forging and are more concentrated at thicker regions of the forgings.
9. *Flakes*: The reason for the occurrence of flakes is the evolution of dissolved gases. Flakes are usually observed on machined surfaces.
10. *Hot tears and thermal cracking*: These are surface cracks occurring due to non-uniform cooling from the casting stage or during heat treatment. In this case, indications are well defined as cracks and are sharp and deep.
11. *Gas porosity*: The magnetic particle test sometimes locates gas porosity and sub-surface blowholes. The indications are not sharp. Some experience is needed to identify these defects.
12. *Weld cracks and other weld defects*: Longitudinal or transverse cracks and parent metal cracks give sharp indications and are easy to detect. However, weld defects such as porosity, slag inclusions, inadequate penetration, lack of fusion and undercuts create fuzzy indications. One should be very careful in interpreting such indications.
13. *Heat treatment cracks (quenching cracks)*: Generally these cracks emanate from sharp corners, fillets, holes, slots or any inherent defects such as seams, which act as stress risers during quenching. These cracks are deep and sharp and give strong indications.
14. *Grinding cracks*: These are seen on highly finished ground surfaces. Cracks are fine, sharp and shallow and occur in groups.
15. *Fatigue cracks*: These occur only in parts that have been in service. Fatigue is a progressive type of brittle fracture, which occurs under cyclic loads. These are mostly surface cracks and give sharp indications, lying in a direction transverse to the direction of local stress.

The appearance of some of these defects is shown in Fig. 5.12.

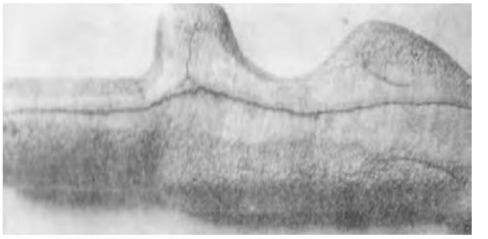
5.8.1 Non-relevant Indications

Sometimes, magnetic particles are attracted to leakage fields that occur for causes other than harmful discontinuities. The cause could be excessive magnetization, sharp variation in dimensions or variation in permeability within the part. Figure 5.13 shows two such examples.

Inclusions



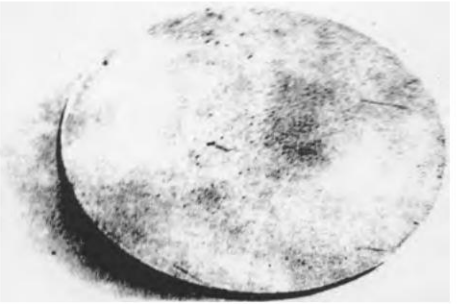
Forging lap



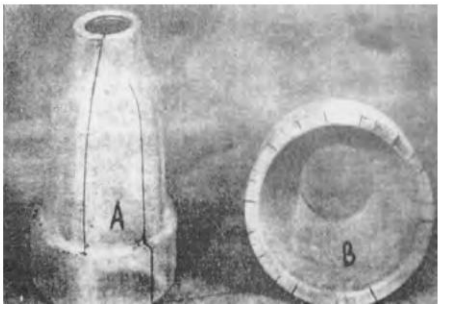
Lap and crack

Grinding crack

Flash line crack



Forging burst



Quench crack

Fig. 5.12 *Some Defect Indications*

(a) Non-relevant indications (b) Magnetic writing

Fig. 5.13 *Non-relevant Indications*

Such indications disappear when the part is demagnetized and again magnetized at a slightly lower value of magnetizing current.

5.9 Effective Applications and Limitations of the Magnetic Particle Test

The magnetic particle test is extensively used for locating and evaluating surface and sub-surface defects in ferromagnetic materials during production, processing and maintenance. A wide variety of industries, e.g. nuclear, aeronautical, shipping, railways, chemical, petroleum, food, paper, etc. utilize this method. However, the surface finish and appropriateness of the technique have a significant effect on the sensitivity and limitations of defect detection.

Table 5.4 gives the range of applications and limitations in flow detection during routine examination.

TABLE 5.4 *Applications and limitations of the magnetic particle test*

Product/Process	*Detection of*	*Limitation of Detection (mm)*	
All ferromagnetic materials, castings, weldments, forging, assemblies, ground and machined components	Surface and sub-surface cracks, grinding cracks, heat treatment cracks, stringer type non-metallic inclusions, porosity, laps and folds, fatigue cracks	Laboratory condition	0.5
		Production condition	1–2
		Service condition	1–2

The limits of detection can be significantly improved with improved facilities and techniques.

6 EDDY CURRENT TEST

6.1 PRINCIPLE OF EDDY CURRENT

When magnetic flux through a conductor changes, induced currents are set up in closed paths on the surface of the conductor. These currents are in a direction perpendicular to the magnetic flux and are called *eddy currents*.

Figure 6.1 illustrates the eddy current.

The basic arrangement for producing eddy currents in a conducting material is shown in Fig. 6.2.

When an alternating current is passed through a coil, a magnetic field is set up around it. The direction of the magnetic field changes with each cycle of alternating current. If a conductor is brought near this

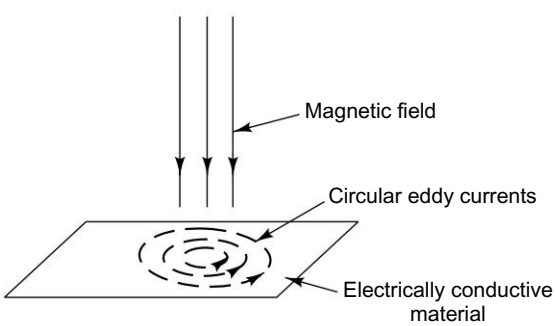


Fig. 6.1 *Eddy Current*

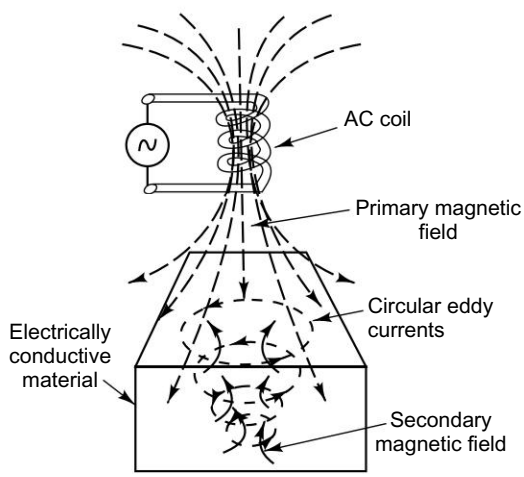


Fig. 6.2 *Generation of Eddy Current*

field, eddy currents are induced in it. The direction of the eddy current changes with a change in the direction of the magnetic field during the cycles of alternating current.

The induced eddy current produces its own magnetic field in a direction opposite to the inducing primary magnetic field. The secondary magnetic field due to the eddy current interacts with the primary magnetic field and changes the overall magnetic field and the magnitude of the current flowing through the coil. This means that the impedance of the coil is altered due to the influence of the eddy current.

During non-destructive testing, changes in impedance are displayed either on a meter or on a CRT screen.

6.1.1 Factors Affecting Eddy Currents

The magnitude and distribution of eddy currents in a given conductor is influenced by the conductivity, the magnitude of the primary magnetic field, the permeability of the conductor, geometrical variations, magnetic coupling, in-homogeneity, discontinuity, the test frequency and skin effect.

In non-magnetic materials, the distribution of eddy currents is strongly influenced by their conductivity. In materials of high conductivity, strong eddy currents are generated on the surface of the conductor. This results in a strong secondary magnetic field, opposing the primary magnetic field. This restricts the penetration of the primary magnetic field into the depth of the material. This means that the depth penetration of eddy currents in good conducting materials is limited. But in poor conducting materials, the depth penetration of eddy currents is comparatively larger as shown in Fig. 6.3.

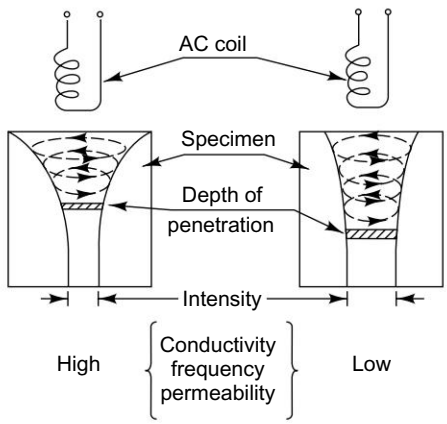


Fig. 6.3 *Depth of Eddy Current Penetration*

The primary magnetic field determines the strength of the induced eddy current as well as the depth of penetration of the eddy current into the material. The effect of magnetic permeability on the eddy current is similar to that of conductivity. Geometrical variations like shape, thickness and the presence of conducting materials in close proximity affects the distribution of eddy currents and the associated magnetic field.

Edges, corners and radii obstruct the circular pattern of the eddy current. This is called the edge effect. It limits the volume distribution of the eddy current and its associated magnetic field as shown in Fig. 6.4.

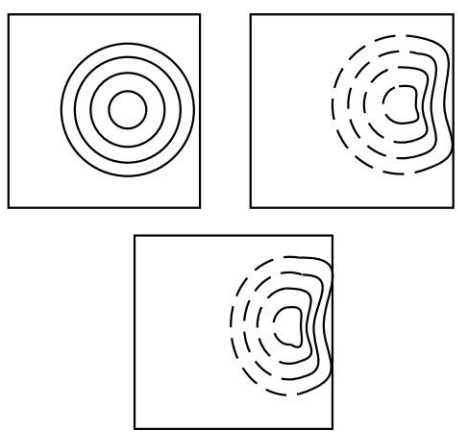


Fig. 6.4 *Distribution of Eddy Current Due to Edge Effect*

In-homogeneities and discontinuities like cracks, inclusions, voids, etc. in conducting materials also affect the circular pattern of eddy currents and the associated magnetic field. Figure 6.5 illustrates the distortion in eddy current distribution due to a discontinuity.

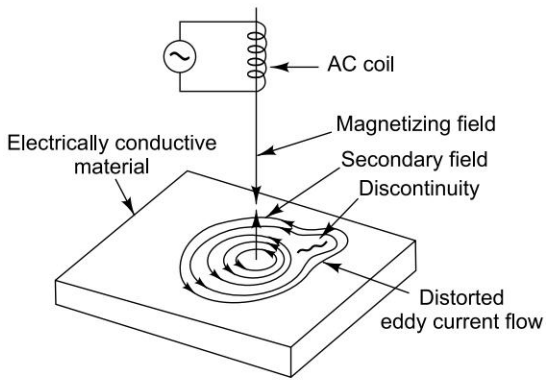


Fig. 6.5 *Effect of Discontinuity on Eddy Current Distribution*

6.1.2 Coupling

Magnetic coupling refers to the interaction of the varying magnetic field of the test coil with the test object. The effect of the primary magnetic field of the coil in inducing an eddy current on the surface of a conductor is strongly influenced by the distance of the coil from its surface. A small distance of separation ensures good coupling.

However, coupling is influenced by such factors as configuration, geometry, surface condition and coating on the surface of the test object. Coupling is of two types: Lift-off and Fill-Factors. Lift-off indicates the effect of separation of the test coil and the test surface. Fill-factor indicates the effect of magnetic coupling when the encircling coil is used to test a cylindrical object. Fill-factor is given by the ratio of the cross-sectional area of the specimen to the effective cross-sectional area of the encircling coil as shown in Fig. 6.6.

Thus, Fill-factor $\eta = \dfrac{\pi D_1^2}{\pi D_2^2} = D_1^2/D_2^2$

where D_1 = Diameter of the cylindrical object
D_2 = Inner diameter of the encircling coil

If the coil is used inside a hollow cylinder, the fill-factor is given by the expression

Fill-factor $\eta = D_2^2/D_1^2$

where D_1 = Internal diameter of the hollow cylinder
D_2 = External diameter of the coil

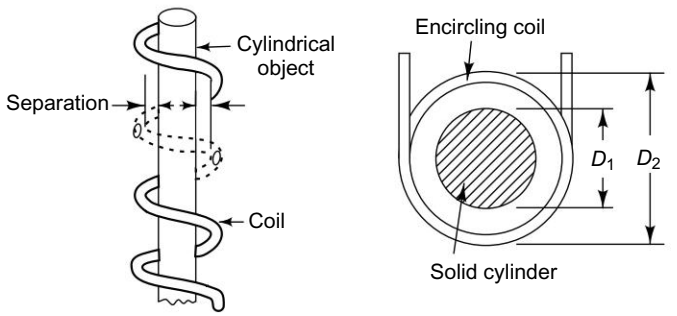
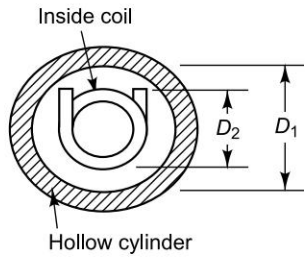


Fig. 6.6 *Fill-factor Encircling the Coil Surrounding the Cylindrical Test Object*

The magnitude of the induced eddy current in an object increases with the frequency of the inducing magnetic field. However, its depth of penetration is low in materials of high conductivity and high magnetic permeability. Eddy current concentration is greater at the surface of the conductor as the depth increases. The depth at which eddy current intensity is reduced to 37% of its intensity on the surface is called *standard depth of penetration* and is given by:

$$\text{Standard depth of penetration} = \frac{1}{\sqrt{\pi f \mu_r \sigma}}$$

where f = Frequency
μ_r = Relative permeability
σ = Electrical conductivity



$$\eta = \frac{D_2^2}{D_1^2}$$

Fig. 6.7 *Fill-factor for a Hollow Cylinder with an Inside Coil*

Figure 6.8 illustrates the relationship between the depth of penetration and the frequency for various materials.

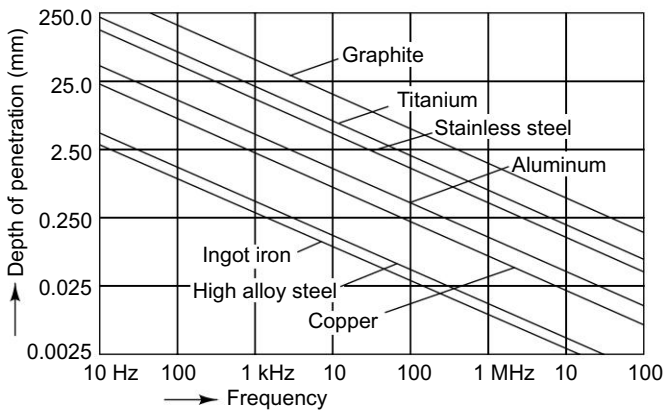


Fig. 6.8 *Depth of Penetration at Various Frequencies in Various Materials*

6.1.3 Impedance Diagram

An impedance diagram is a graphical representation of the effect of eddy current variables on the test coil impedance. The variables are electrical conductivity, dimensional variations and the magnetic permeability of the part. In addition to these, frequencies, discontinuities and coupling factors also influence the impedance of the coil.

The *x*-axis of the impedance diagram represents the resistive component of the coil's impedance, while the *y*-axis represents the inductive component of the coil's impedance. Impedance diagrams are prepared for each of the variables mentioned.

To eliminate the effect of construction or geometry of the coil, the impedance diagrams are normalized. This is done by using the ratio of the inductance of the coil L with the specimen, and L_0 without the specimen (L/L_0). This procedure makes the presentation of information independent of the physical parameters of the coil. In a normalized impedance diagram, the *x*-axis represents the ratio $(R–R_0)/\omega L_0$ and the *y*-axis represents the ratio $\omega L/\omega L_0$

where R_0 = Resistance of the coil without the test specimen
R = Resistance of the coil with the test specimen
L_0 = Inductance of the coil without the test specimen
L = Inductance of the coil with the test specimen
ω = Angular frequency of the applied AC

Further, in order to make the impedance diagram independent of the conductivity, permeability and diameter of the test piece, impedance diagrams are plotted for the ratio f/f_c instead of the existing frequency 'f'. Here, f_c is called limiting frequency and is defined as

$$f_c = \frac{2}{\pi\sigma\mu d^2}$$

where σ = Electrical conductivity
μ = Magnetic permeability
d = Diameter of the test piece

The estimated value of f_c is given as $5066/\mu\sigma d^2$.

6.1.4 Effect of Coupling on Impedance Diagram

Effect of Lift-off

It has been explained earlier that the separation between the test object surface and the test coil is a measure of the lift-off. A large distance of separation (large lift-off) leads to a weak induction of the eddy current, resulting in small changes in the impedance of the coil. A small separation (small lift-off) leads to a strong induction of the eddy current, resulting in large changes in the impedance of the coil.

Other variables remaining constant, a variation in lift-off produces a significant variation in the impedance of the test coil. This effect may mask the variation in impedance of the test coil due to property variation or due to the presence of a defect in the text material. It is necessary, therefore, from the viewpoint of the practical application of eddy currents for nondestructive testing, to know the effect of the lift-off on the impedance of the coil. Figure 6.9 shows an impedance diagram for different values of lift-off.

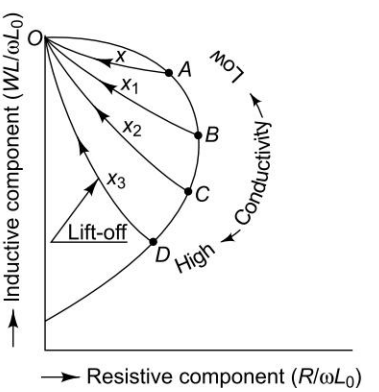


Fig. 6.9 *Effect of Lift-off on the Impedance of the Coil*

In the figure, O represents the impedance of the coil when it is in the air, a good distance away from the test specimen. As the coil approaches the test object with conductivity A, the impedance locus is OAX. Similarly, for materials of conductivity B, C, D, etc. the loci are OX_1B, OX_2C, OX_3D, etc. for various values of lift-off. When the coil touches the part, the point of intersection with the impedance locus of the variable under consideration (conductivity in the present case), namely points A, B, C, D, etc. gives the impedance of the test coil-test piece combination.

Effect of Fill-factor

The impedance diagram is plotted in a similar manner for different values of fill-factor (η) as Fig. 6.10 illustrates.

6.1.5 Effect of Magnetic Permeability on Impedance Diagram

The current in a test coil induces magnetic flux in a conductive material present near it. The distribution of magnetic induction is uneven along the cross-section of the material. This uneven distribution of magnetic induction leads to an uneven distribution of the eddy current, resulting in the charge of impedance of the test coil. If no conducting material is present near the coil, the flux density is given by:

$$B_0 = \mu_0 H_0$$

where H_0 is the field due to the coil

μ_0 is the permeability of free space

B_0 is the flux density

If a conducting material is present, the flux density in the material changes to B_1 (say) and is no longer constant over the cross-section due to non-uniformity of eddy current density within the material. The changed flux density B_1 is given by:

$B_1 = \mu_{\text{eff}} \cdot B_0$, where μ_{eff} is the changed permeability due to presence of the conducting material.

Figure 6.11 shows the effect of changes in permeability on the impedance diagram.

The test frequencies are expressed as ratio f/f_c = 1, 2, 3, 4….

The curve *ABCD* represents various f/f_c values, f being the frequency of the existing current.

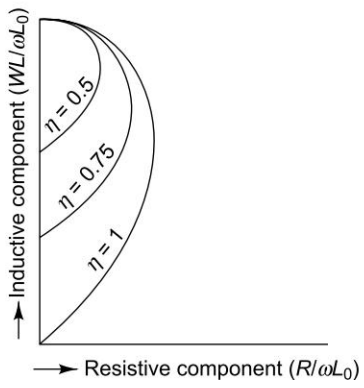


Fig. 6.10 *Impedance Diagram for Different Values of Fill-factor*

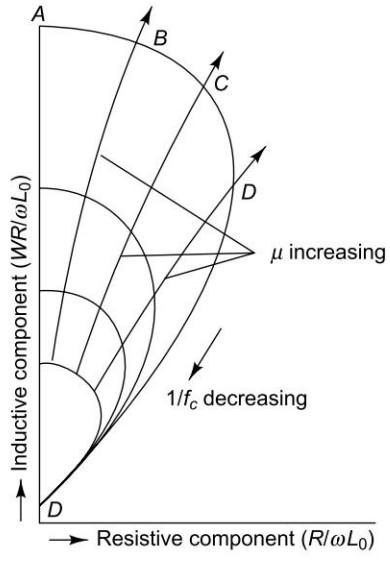


Fig. 6.11 *Effect of Permeability on Impedance Diagram*

6.1.6 Effect of Crack on the Impedance Diagram

The effect of crack depth from the test surface on the impedance diagram is shown in Fig. 6.12.

With increasing depth of crack from the test surface, the impedance loci are *A, B, C*: *A* being a crack near the surface and *C* being a crack at greater depth.

Note that a change in impedance includes a change in magnitude as well as phase.

From the viewpoint of the test, it is necessary to keep all the eddy current variables constant, except the one of interest, and study the change in magnitude as well as phase.

Phase studies help to separate the eddy current responses of specific variables like permeability, cracks, thickness, conductivity or magnetic coupling from others.

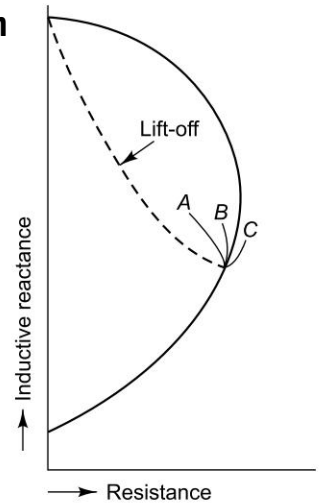


Fig. 6.12 *Effect of Crack Depth from the Surface on the Impedance Diagram*

6.2 Eddy Current Test System

Any eddy current test system consists of:

- An oscillator to provide the alternating current for exciting the test coil
- A combination of a test coil and a test object to generate information in the form of an electrical signal. Varying the property of the test object modulates the impedance magnitude of the coil
- Signal processing and display

Figure 6.13 gives the block diagram of an eddy current test system.

The oscillator provides an alternating current of the required frequency to the test coil, which generates an eddy current in the test object. Test object variables like conductivity, permeability or discontinuities modulate the test coil impedance. The modulated impedance signal is processed and displayed over a readout mechanism like meters, CRT, relays, recorders, etc.

There are four basic types of eddy current instruments that carry out the following measurements:

- Measurement of the change in magnitude of the total impedance of the test coil, regardless of phase

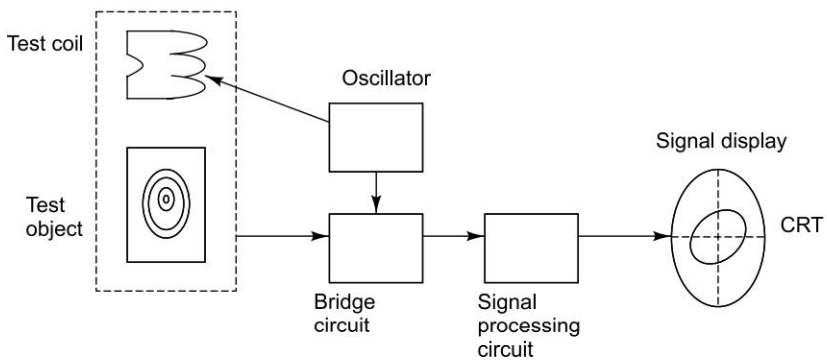


Fig. 6.13 *Block Diagram of Eddy Current Test System*

- Phase-sensitive measurement, which separates the resistive and reactive components of the test coil impedance
- Measurement of the resistive component of the test coil impedance
- Measurement of the inductive component of the test coil impedance
- Measurement of the total impedance of the test coil, regardless of phase

6.2.1 Sensing Element and Test Arrangements

The sensing element (also called the test coil) serves as the main link between the test instrument and the test object. It establishes a varying electromagnetic field, which induces the eddy current in the test object and increases the magnetic effect in magnetic materials. It also senses the current flow and magnetic effect within the test object and feeds the information to the signal analysis system.

The test coils are essentially of three types as discussed next.

Encircling Coil

The test coil is in the form of a solenoid into which the test part is placed as shown in Fig. 6.14.

Test objects in the form of rods and tubes are examined conveniently. The entire exterior circumferential surface of the test object covered by the coil is scanned. This arrangement also helps high-speed testing. However, it is not possible to exactly locate the defect on the circumference.

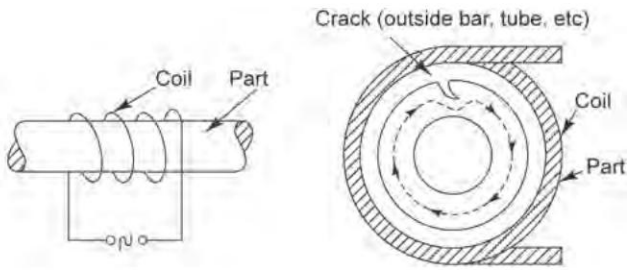


Fig. 6.14 *Encircling Coil*

Coil Inside the Test Object

Here the test coil is in the form of a winding over a bobbin. The coil, thus wound, passes through test objects like tubes, bolt holes, etc. and scans the inner circumferential surface of the test object as illustrated in Fig. 6.15.

This arrangement evaluates the entire internal circumferential surface at a time, which is not accessible to any other optical method of inspection. However, it is not possible to exactly locate the defect over the circumference examined.

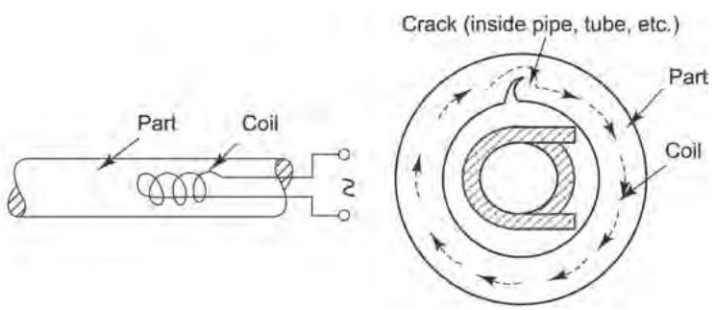


Fig. 6.15 *Coil Inside the Test Object*

Surface Coil

Here, the test coil is in the form of a spring-mounted flat probe or a pointed pencil-type probe, which scans the surface of the selected location of the test object. The arrangement is shown in Fig. 6.16.

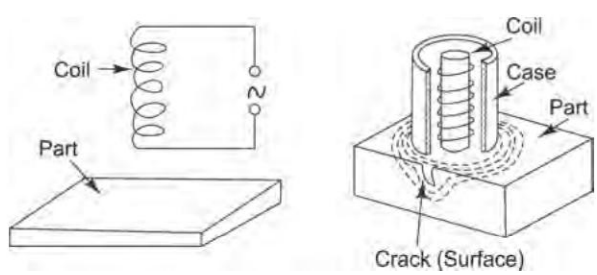


Fig. 6.16 *Surface Coil*

The advantage of this arrangement is that it is possible to pin-point the defect.

In eddy current testing, the coils are incorporated in a bridge circuit, which can be balanced on any acceptable specimen characteristics. Whenever an impedance change occurs due to the test object parameters of interest, there is an imbalance, which can be seen on a convenient display system. Figure 6.17 shows a simple bridge circuit.

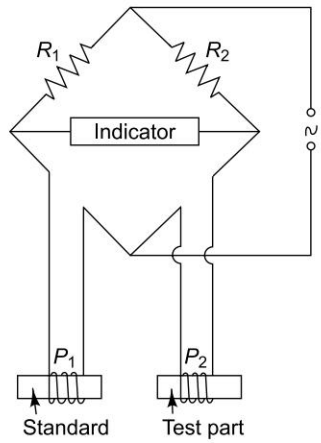


Fig. 6.17 *Simple Eddy Current Detector*

Such testing units are used for material comparison and crack detection.

In more elaborate circuit units, both magnitude and phase of the test coil-impedance change are measured. Phase analysis is based on studying the phase difference between two signals. The current across a resistance is in phase with the applied voltage, whereas the current across an inductor lags behind the voltage. If the coil is empty, the lag is 90°.

If a specimen is passed through the coil, the lag is less than 90°. If the specimen's properties like conductivity, dimension, permeability, etc. change, the phase lag changes accordingly.

If we study the conductivity variation of a number of samples with varying conductivity but same dimensions and permeability, it is seen that measured values of impedance vary with changing conductivity, as shown in Fig. 6.18(a).

Similarly, if conductivity is the same and only dimensions or permeability of the specimen vary, the variation in impedance is as shown in Fig. 6.18(b).

If vectors representing conductivity, dimensions and permeability are superimposed as shown in Fig. 6.18(c), it is clearly seen that the conductivity vector is moving in a direction perpendicular to the vectors of dimensions and permeability. The angle between the two vectors θ is known as the phase angle. Note that the vectors are in two different quadrants.

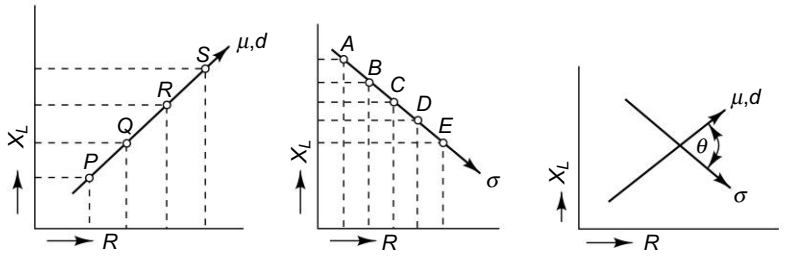


Fig. 6.18 *Variation in Impedance due to Change in Conductivity, Dimensions or Permeability*

The vector point displayed on an *X–Y* storage oscilloscope represents the magnitude and phase of the impedance change. If E_1 and E_2 are two voltages, the resultant voltage E_r (by vector addition) is indicated as a point. The position of the point on a CRT depends on the electrical and magnetic variable components

E_1 (resistive component of voltage) and E_2 (inductive component of voltage). The movement of the spot during the lift-off of the probe from the surface identifies the permeability axis, whereas the deflection due to defect and conductivity changes, takes place along an axis perpendicular to the permeability axis as shown in Fig. 6.19.

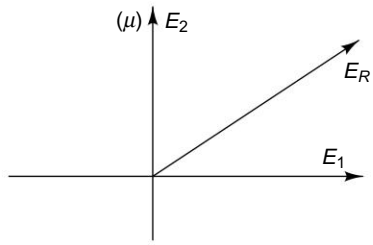


Fig. 6.19 *CRT Display of Eddy Current Detection*

The basic block diagram of a typical vector point method is shown in Fig. 6.20. The oscillator supplies an exciting current to both primary P_1 and P_2. The oppositely wound secondary is connected to a single processor unit, where both resistive and reactive components of voltage are controlled to move the vector point across the CRT screen. In this way the impedance diagram can be produced on a CRT screen.

The processed signal output is driven through a phase shifter. By adjusting the phase shifter, the reference voltage can be changed as desired.

Initially, the adjustment is done with a test part similar to the reference standard. This test object is replaced by a part whose parameter is to be checked; by adjusting the phase shifter, the variables of interest alone can be studied. The test system is also provided with magnetic saturation devices. When the magnetic variable is separated by suitable saturation, the dimensional variation can be studied.

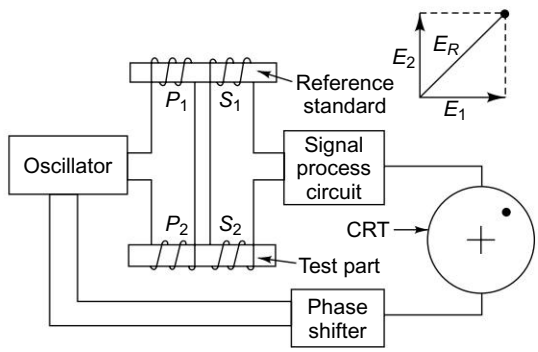


Fig. 6.20 *Basic Arrangement for Vector Point Method*

Another example of the use of this method is the ellipse method. Here, the voltage from the primary coil P_1 P_2 is fed to the X-plate of the CRT and the voltage across the secondary S_1S_2 is fed to the Y-plate. Since the two voltages of the same frequency are alternating, the figure on the CRT screen is an ellipse. The shape of the ellipse depends on the phase difference between the voltages. The size and shape of the ellipse can be related to a displacement on the impedance diagram and correlated to a variation in conductivity, dimension or to the presence of defects.

Typical ellipse patterns are shown in Fig. 6.21.

6.2.2 Standardization and Calibration

Eddy current test methods are applied on 'Go/No Go' basis by calibrating the test system against a pre-fabricated standard with known magnitudes of variation of the parameters desired to be measured. The standard test specimen is identical to the test component except in the parameter being measured. Artificially fabricated standards may contain notches, slots, holes, etc.

Reference standards are used to standardize the test system under operating conditions to ensure sensitivity, reproducibility of results and for periodic evaluation of the system.

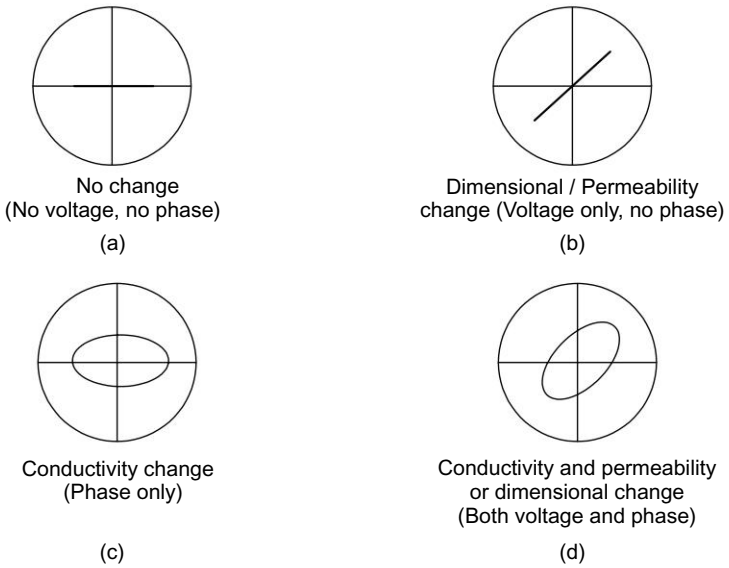


Fig. 6.21 *Typical Ellipse Patterns*

Acceptance Standards

Acceptance standards are used to establish an acceptable level in a test component under standardized conditions. For practical applications, reference standards are employed to establish quality control checks for uniformity of response, which can be related to the minimum size of the crack/defect to be detected.

The following standards, with various types of artificial discontinuities, are widely used in industry.

Defect Measurement: Tubes

Longitudinal notches are made either by milling or by electro discharge machining (EDM) on the outer and inner surfaces of a tube having the same material composition as the tubes under examination. The depth of the notch is specified as a percentage of wall thickness—10%, 12.5%, 20%, etc. The notch width is variable and can be specified. The length of the notch is 6 mm, 12.5 mm, 25 mm, etc. A typical specimen is shown in Fig. 6.22.

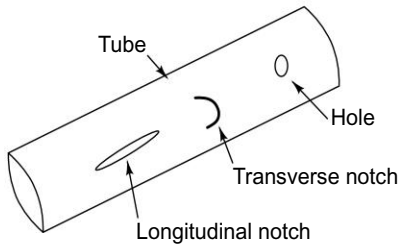


Fig. 6.22 *Typical Notch Standard*

Transverse notch A milled or EDM transverse notch is located at the outer or inner surface or on both surfaces. The notch depth is specified as a percentage of the wall thickness of the tube, the width is variable and is preferably kept below 1.5 mm.

Holes Holes are drilled radially through the tube thickness. The diameter of the hole is specified as a percentage of wall thickness or arbitrary sizes may be selected, based on the end use of the test component and its acceptance criteria. Normally, holes of diameters ranging between 20–50% of tube wall thickness are used.

Flat Components

Calibration standard material should have almost the same composition as that of the test component. Milled or EDM slots of depth 0.2 mm, 0.5 mm and 1.0 mm are provided on the standard specimen. The slot width is uniformly maintained at 0.10 mm. A typical flat test standard is shown in Fig. 6.23.

Standards selected for eddy current testing should satisfy: Low cost of fabrication, ease of fabrication, convenience of fieldwork and reproducibility of results.

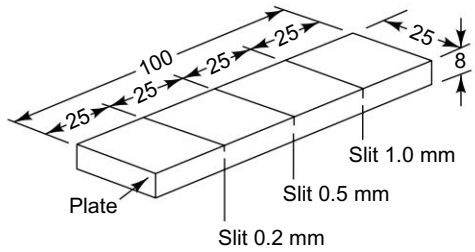


Fig. 6.23 *Defect Standard for Flat Test Objects*

6.2.3 Test Coil Selection

The selection of a test coil is influenced by the following factors:

- The nature and shape of the specimens to be tested
- The type of information, sensitivity and resolution required
- The volume of tests required

Since the depth of eddy current penetration is a function of frequency, conductivity and permeability, the frequency becomes an important parameter for selecting the test coil for specimens of known conductivity and permeability. High frequency probes are used for the detection of surface and just-below-the-surface defects. Low frequency probes are used to detect corrosion or cracks located deep down in the material. Figure 6.24 gives a general guideline for frequency selection.

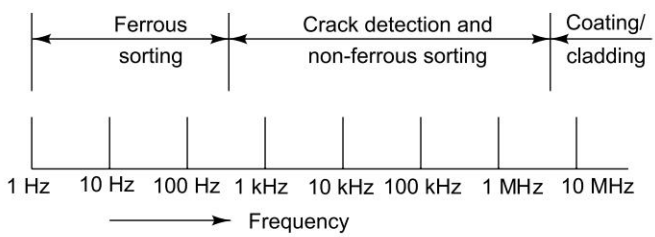


Fig. 6.24 *Guideline for Selection of Frequency*

6.3 Applications of Eddy Current Testing

Eddy current test methods are put to a variety of applications. Broadly, eddy current applications can be grouped into—conductivity measurement (shorting, hardness, heat treatment, alloy segregation, case depth assessment, etc.), discontinuity testing (cracks, dimensional changes, surface condition, etc.) and thickness measurement (coating, plating, sheet metal gauging).

The electrical conductivity of a material is expressed as a percentage IACS (International Annealed Copper Standard), in which a specific grade of high purity annealed copper is arbitrarily assigned 100% conductivity. All other metals can be identified according to this standard. Many factors like temperature,

composition, heat treatment, microstructure, grain size and mechanical properties influence the conductivity of a material. Hence, studying the variation in conductivity helps in indirectly assessing these properties and controlling variables such as composition, heat treatment, metal working, etc. To measure the conductivity of a magnetic material, it is subjected to a strong magnetic field, to its saturation value so that the magnetic characteristics of permeability, hysterisis, etc. do not interfere with conductivity measurement.

In-homogeneities like cracks, inclusions, voids, scamp, laps, etc. appreciably change the normal circular eddy current flow pattern and can be detected by the eddy current test coil.

Further, phase changes are unique for several eddy current inspection parameters. By determining the phase change of an eddy current response, it is possible to isolate the response of specific variables such as conductivity, lift-off, thickness, permeability and cracks.

In so far as coating thickness measurement is concerned, the eddy current system measures the variation in impedance it causes. The basic requirement for this thickness measurement is that the electrical conductivity of the coating should differ significantly from that of the substrate. The accuracy and range of metal thickness that can be measured with the eddy current system depends on the electromagnetic properties of the material and the capability of the test system. Increasing the conductivity and permeability increases the accuracy of measuring a thin specimen but decreases the effective range of measurement and accuracy at greater depths. The main purpose of using an eddy current to measure the total thickness of a metal part is to detect corrosion, erosion, wear out, etc.

6.4 Effectiveness of Eddy Current Testing

Eddy current testing is normally used for the study of surface and sub-surface anomalies in conducting materials. The method is complementary to ultrasonic testing for detecting defects close to the surface. It is also complementary to the liquid penetrant inspection, which cannot reveal sub-surface defects. The method, however, cannot be used on non-conducting materials. Also, local variations in conductivity and permeability of an acceptable nature may interfere with accurate detection of discontinuities. The measurement of metal coating thickness is also difficult unless a substantial difference in conductivity exists between the coating and the substrate under normal operating conditions. It is possible to detect defects of sizes as indicated in Table 6.1. The detectability of defects is, however, influenced considerably by the surface condition, material properties, test equipment capability, the frequency used and the test environment.

TABLE 6.1 *Approximate sizes of detectable defects*

Defects	***Detectable Size of Defects (mm)***	
Surface and sub-surface anomalies	Laboratory condition	0.25
	Production/Processing	1.0
	Service condition	1.0 (fatigue cracks)

At high frequencies (2 MHz or more) and in good conductors, surface cracks of length 15–20 microns can be detected. It is possible to improve limits of detection significantly with improved facilities and techniques.

7 Other Topics

7.1 Thermal Infrared Testing

If we look at the electromagnetic spectrum, we find that the temperature increases from the violet region of the spectrum to the red region and beyond as shown in Fig. 7.1.

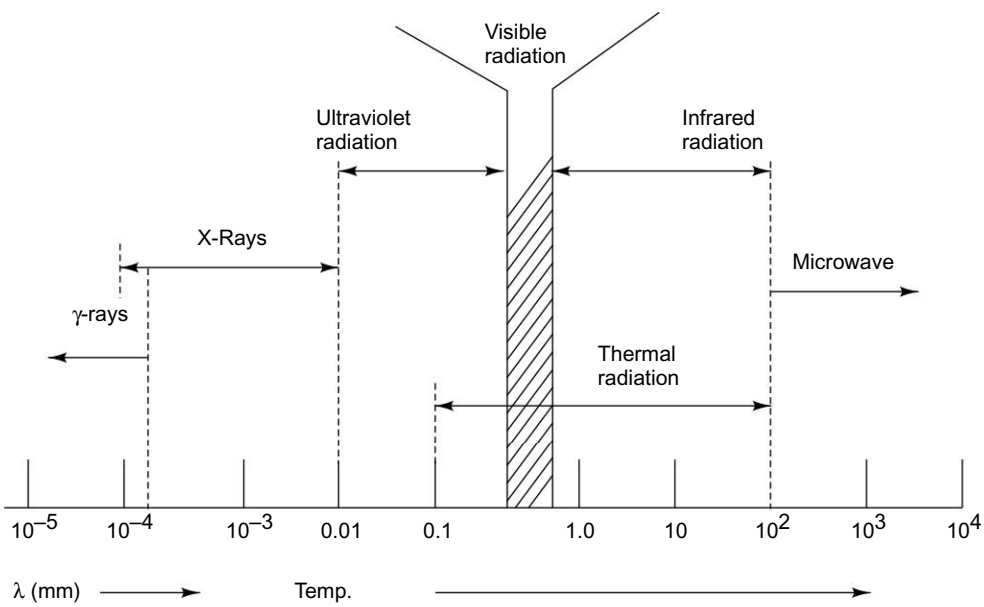


Fig. 7.1 *Electromagnetic Spectrum*

The region beyond red is called the infrared region. When an object is irradiated by infrared radiation, it gets heated and heat flows on the surface or through the thickness of the object from the warmer to the cooler region. This results in temperature variation and is related to the pattern of heat flow. The transfer of heat energy continues from the warmer to the cooler region, till equilibrium is reached. This energy is detected and monitored by infrared cameras.

The flow of heat is affected by such factors as: density, specific heat, thermal conductivity, diffusivity, surface finish, surface cleanliness, voids, inclusions, metallurgical anomalies and process parameters related to the fabrication of the object.

Using infrared as an NDE tool involves the measuring or mapping of surface temperature, which leads to the detection of defects on the material, in-homogeneity/anomalies.

Test objects intended for infrared testing are classified as passive and active. Passive objects are usually at a higher temperature and do not require external heating.

The applications of passive infrared testing include the detection of forging laps, the state of furnace linings, predictive maintenance, the frictional wear and tear of machines, fire detection, road traffic monitoring, testing electronic devices for local overheating and soldering joints. Apart from these, the application areas also include agriculture, biology and medicine.

Insofar as active objects are concerned, an external stimulus is required for heating or cooling and to create a temperature variation. Some of the heating methods are laser heating for repeated, focused heating; heating using a lamp; flash lamp and using an air jet for heating or cooling.

The heating system generates thermal waves inside the test object. The radiated infrared energy is observed and studied with the help of thermal imaging instruments. In many systems, the heating and data acquisition systems are integrated. In certain systems, vibro-thermography is used, where the object is vibrated externally and heat is produced by friction at defect locations. This helps in the detection of defects that are not normally visible by other infrared thermographic methods.

Thermal imaging instruments receive infrared energy and convert it into a temperature profile. A thermal image is shown as a grayscale image, where hot regions are white, cold regions are black and intermediate temperatures are variations of gray. To make interpretation easy, thermal images are artificially colored. Digital image processing further improves the quality of images. However, the quality of the image is influenced by non-uniformity in emissivity caused by surface roughness and the state of cleanliness of the surface.

Like any other NDE method, reference standards are essential to ensure consistent performance of temperature sensors and equipment.

Thermography has a wide range of applications including the testing and evaluation of furnaces, ovens, cryogenic tanks, bearings, heat exchangers, process controls, entrapment of water or fuel in honeycomb structures, detection of over-heating in electrical devices and the detection of corrosion, fatigue cracks and poor soldering in space shuttle components.

The main advantages of infrared testing are that the system does not require any couplant, inspection is fast and interpretation of the indication is simple. However, the system has certain limitations. For example, the system is expensive; only limited thicknesses of the object can be examined; it is difficult to obtain a uniform heating system over large areas. If there is no change in thermal properties, defects cannot be detected. Further, the range of applications of thermography is limited to 0.8 to 20 mm.

Research efforts are being made to improve the system by incorporating advanced data collection and data processing methodologies.

7.2 Acoustic Emission

The phenomenon of generating transient elastic waves during the release of energy from localized sources within a solid material is called Acoustic Emission (AE). Dislocations resulting from plastic deformations cause AE. Plastic deformation takes place when materials are stressed beyond their elastic limit. This could happen during the initiation of a crack, the growth of a crack, phase changes in the materials and fiber breakage or fiber-matrix debond in composites.

The elastic waves generated in this manner propagate in all directions and reach the surface of the material, where they are detected with the help of piezo-electric transducers. A typical AE setup is shown schematically in Fig. 7.2.

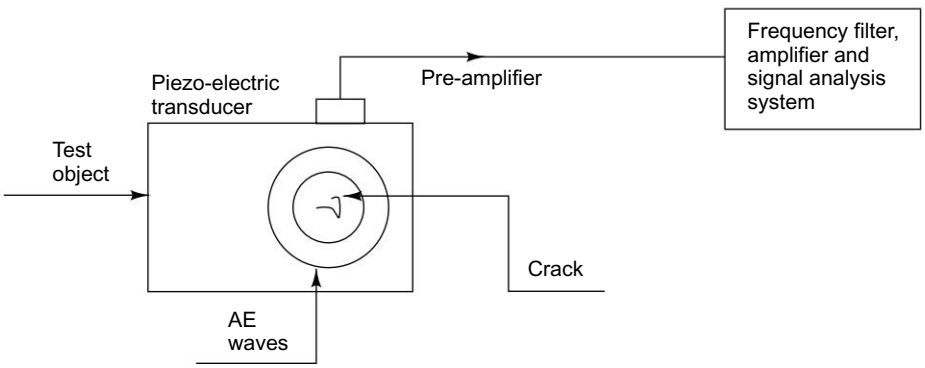


Fig. 7.2 *AE Setup*

The piezo-electric transducer is directly attached to the test object with a coupling medium and secured with tape. The voltage output from the transducer is fed into the pre-amplifier, which is placed close to the transducer. Sometimes the transducer and pre-amplifier are built in one unit. The pre-amplifier eliminates mechanical, acoustical and background noise. However, it also generates electrical noise, which limits the sensitivity of the system. The pre-amplifier signal is passed through a variable band pass filter to the main amplifier connected to a signal analysis system. The signal analysis system produces a signal each time the amplifier voltage signal exceeds a selected threshold level.

The following parameters are used to identify AE events:

- Peak amplitude — The peak of the signal
- Arrival time — The time when the peak signal crosses the threshold signal
- Duration time — The time between the first threshold crossing and the peak amplitude
- Ring count — The number of threshold crossings

In addition, load, deformation pressure and temperature are also recorded as input parameters.

The major steps involved in AE testing are: detection of AE activities, which occur during the onset of the damage; estimation of the AE burst, which indicates the severity of the damage and the AE source, that is, the location of the damage.

To locate the source of an AE event, a number of transducers are usually arranged in a predetermined geometrical form on the test object. A computer-controlled signal analysis system computes the arrival

time of the AE signals at individual transducers. By knowing the wave velocity and arrival times at the transducers, the AE source can be located.

Like any other NDE method, an AE signal needs to be calibrated. This is done by first producing a predefined signal. This signal is produced by breaking a pencil graphite lead, which produces an acoustic signal similar to a natural burst.

AE has been put to a wide range of applications for the detection of faults or leakage and for monitoring welding and the progress of corrosion and fatigue. The areas of application include:

- Pressure vessel testing
- Structural integrity test
- Production quality control
- Material testing
- Pipeline monitoring
- Railroad and bridge monitoring
- Leak detection
- Aircraft life assessment
- Nuclear component inspection
- Testing of composites and ceramics
- Rocket motor testing

The main advantages of AE testing are one, AE is a relatively rapid inspection tool for locating damage and is capable of providing an early warning of a sudden failure; two, it is a global monitoring tool and does not require access to the complete monitoring area.

However, the method has certain limitations. AE is produced only when the damage is active. In most cases, the method is only qualitative. AE signals are usually weak, which makes signal discrimination difficult. Other problems are related to noise, reliability and difficulty in analysis of the source function and waveform. More research and development is needed in this area.

7.3 Leak Testing

Leakage implies the escape of liquid or gas from a pressurized or evacuated enclosure or system. It occurs due to pressure differences between the inside and outside of the system or enclosure. It may also occur due to permeation through a barrier.

Leak testing is important for the safety and performance of the system as well as to prevent environmental pollution.

The objective of leak testing is to locate and/or measure the amount of leak—liquid or gas flowing through a discontinuity (e.g. a crack, hole or tiny pore).

The major steps in a leak test are:

- Locating the leak
- Measuring the rate of leakage
- Monitoring the leakage for the maintenance of the system

The commonly used units of leakage are:

- Standard cubic centimeter per second (std. cm^3/s)
- Standard atmosphere cubic centimeter per second (atm. cm^3/s)

These units are equivalent. The unit used in the vacuum leak test is torr liter per sec. The S1 unit is Pascal cubic meter per second (Pam^3/s).

It needs to be clear that nothing can be completely free from leakage. An important question that needs to be answered is—what system can be considered leak-safe or with acceptable leakage?

In this regard, some norms of safe leakage or acceptable leakage are accepted under normal operating conditions. The following table gives the acceptable leakages for some substances.

TABLE 7.1 *Acceptable leakage*

Substance	*Acceptable Leakage (std. cc/sec)*
Water	1×10^{-3}
Gasoline from storage tanks	1×10^{-4}
Gas from pipelines	1×10^{-5}
Leakage in a tanker	1×10^{-6}

Leakage depends upon the type of fluid, the geometry of the discontinuity and the sensitivity of the detecting instrument.

A number of methods are used for leak testing. Some of the methods are: hydrostatic, immersion, liquid film, colorometric, penetrant liquid, pressure change, helium mass spectrometry and acoustic emission. A short description of the methods is given below:

7.3.1 Methods of Leak Testing

1. Hydrostatic test — The hydrostatic test is performed to examine leaks in welded pressure vessels, piping and fitting sections of pressure vessels. The method consists of filling the pressure vessel with water under high pressure and observing the seepage of water from the location of the discontinuity. The method is simple but time consuming.
2. Immersion test — In this method, small vessels are pressurized with any gas and the vessel is immersed in water or water with an additive. Escaping bubbles from leak locations are observed. The method locates small leaks. It is essential to ensure that the immersion liquid does not attack the vessel chemically.
3. Liquid film test — In this method, the vessel under test is pressurized with a gas. A thin film of soap solution or any other suitable liquid is applied on the outer surface of the vessel on suspected areas. The gas escaping from the discontinuity causes the thin film of liquid on the surface of the vessel to bubble. The bubble pinpoints the leak and also gives an idea of the size of the leak. The vessel needs to be cleaned after the test.
4. Pressure change test — In this method the closed container is pressurized and the pressure of the system is observed for two hours or more. After this time, the initial and final pressures in the container are compared. A change in pressure is indicative of a leak in the system. It is not possible to locate the leak spot. The test could be time consuming.

5. Tracer gas test

(i) Colorometric method

Colorometric methods are used to detect a leak in double-walled tanks, pressure vessels and vacuum vessels. The method makes use of a tracer gas like ammonia, because of its ability to penetrate leaks. The tracer gas is introduced into the vessel at a pre-determined pressure. A thin coat of indicator developer powder is applied on the outer surface of the vessel around suspected areas like seams, welds and joints. Over a period of time, the tracer gas diffuses into the system. The gas escaping from the leak reacts with the developer powder and changes its color, indicating the location of the leak. The system needs to be cleaned after the test.

(ii) Helium mass spectrometry

Helium mass spectrometers make use of helium or other tracer gases (e.g. nitrogen, oxygen or carbon dioxide) to detect very small leaks. This method is used to detect and measure leaks from hermetically sealed devices, vacuum chambers or cryogenic tanks and a large number of heat exchanger tubes. In this method, the test chamber is pressurized with helium or a helium-air mixture. The chamber is evacuated and helium is made to pass through leak points and enter the surrounding vacuum. Helium is ionized by an electron beam and subjected to a magnetic field, which deflects the ions onto a detector. As the helium ions strike the detector, a minute current flow is generated, which is then amplified. This current is proportional to the leak rate and is recorded on the leak rate indicator.

6. Acoustic emission test

The determination of leaks by acoustic emission depends on the fact that leaks through a discontinuity become noisy when there is a fluctuation of pressure associated with turbulence. These pressure fluctuations generate stress waves. These waves propagate through the structure of the container and can be picked up by remote acoustic emission sensors and analyzed for the location and characterization of the leak. The leak depends upon the type of fluid, the geometry of the discontinuity and the sensitivity of the detecting instruments.

8

Non-Destructive Test of Fiber Re-Inforced Composites

Fiber re-inforced composites are susceptible to fabrication defects, impact damage, moisture absorption, variability in material properties.

It is often required to produce evidence through NDT methods to establish integrity of structures, repeatability of manufacturing process to ensure design stipulated strength, stiffness, thickness, variation and material homogeneity. Usually a combination of complementary NDT is used for this.

Two conventional methods of NDT, namely—Ultrasonics and low energy Radiography have been successfully applied to test, evaluate and certify composites.

Other methods that have used to varying degrees of success are:

1. Visual Methods
2. Coin tap method
3. Resonance based methods (Fokkar Bond Test)
4. Thermography
5. Acoustic Emission
6. High Frequency Eddy Current

8.1 Specific Methods

Ultrasonics:

This is the most preferred method for evaluation of composites. The method is effective in detecting delaminations, voids, porosity and in some cases other flaws like broken fibers and inclusions. The defect is presented in A, B or C-scan form. Fig. 8.1 illustrates the defect presentation forms.

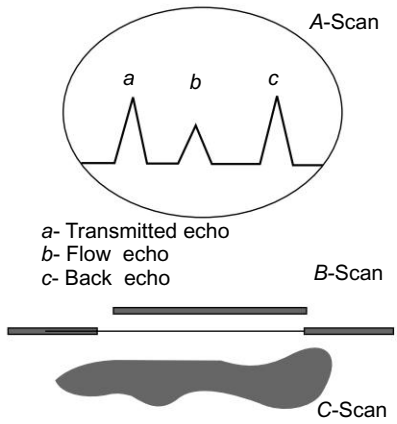


Fig. 8.1 *A, B and C—Scan Presentation of Defects*

It may be noted that, A-Scan records both amplitude and depth of defect on the CRT, B-Scan gives sectional view of the defects and C-Scan gives plane view of the defect, projected on a plane at right angle to the axis of the ultrasonic beam.

Two common test methods used are:

(a) Through Transmission Method

In this method, ultrasonic waves are passed through the test sample to a receiver on the opposite side. An acoustic coupling between transducers and the test object is applied. The most common couplant is water, used either by immersing the test object or with squirters at the transducer heads. Any air interfaces in the material—gaps, voids, porosity, etc., cause internal reflections, because the acoustic impedance of air is very different from that of the host material. Measuring attenuation of the sound energy transmitted through the structure indicates the presence of defects. Technique is illustrated in Fig. 8.2.

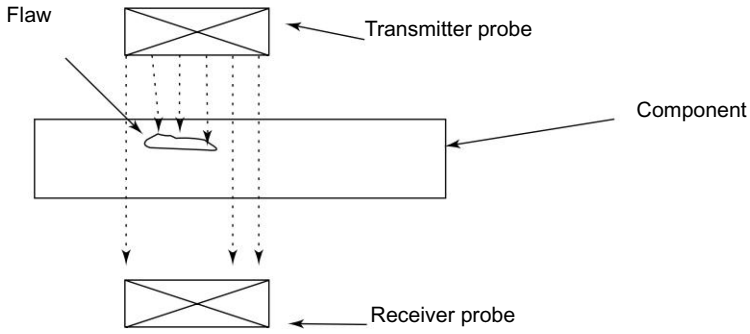


Fig. 8.2 *Through Transmission Technique*

This method is employed to examine monolithic as well as honeycomb structures for detection of anomalies like—gaps, voids, delamination, disbond and internal assembly condition. It is possible to assess size of the defects, but the method cannot provide depth information of the detected defects/

anomalies. The technique of through transmission is preferred, where only detection of defects is required. The technique is not suitable for curved components. Ultrasonic frequencies used are in the range of 1 MHz-10 MHz.

(b) Pulse-echo Method

In this method, ultrasonic waves travel through the test object and reflect from the back surface. Both attenuation of ultrasonic energy and time of travel of an ultrasonic pulse to travel twice through the test object are measured. A component is generally scanned by moving the transducer back and forth across the surface, then shifting by indexing a small distance after each pass. Pulse-echo method gives more information about the size and depth of flaws. With this method, it is possible to detect and evaluate:

- Discrete and volume dispersed defects
- Depth location of defects
- Elastic modulii of the material
- Thickness variations

Successful application of the method requires careful study and appreciation of the effect of probe characteristics, e.g., pulse length, near zone, far zone, signal gating, etc. The method is illustrated in Fig. 8.3.

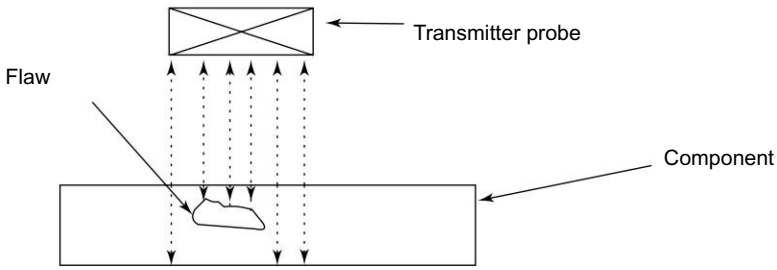


Fig. 8.3 *Pulse Echo method*

(c) Other Ultrasonic Techniques Include

Double transmission or reflector plate method. In this method, ultrasonic waves are passed through the test sample to a suitable reflector plate, such as a polished metal or a glass plate. The ultrasonic waves then pass through the test sample a second time to the original transducer. The method is used with relatively flat and thin structures that can be immersed. This technique is illustrated in Fig. 8.4.

A more sensitive oblique incidence, shear wave immersion technique is illustrated in Fig. 8.5. Here a suitable incident angle of a longitudinal wave is selected. The shear wave produced (by mode conversion) has excellent sensitivity to subtle defects, such as interfacial weakness.

It is to be noted that shear waves are confined only within the material. Longitudinal waves travel through water. A good amount of work is necessary in instrumentation to rotate the sample in water and ensure correct insonification of the test specimen. Longitudinal and shear waves propagate without

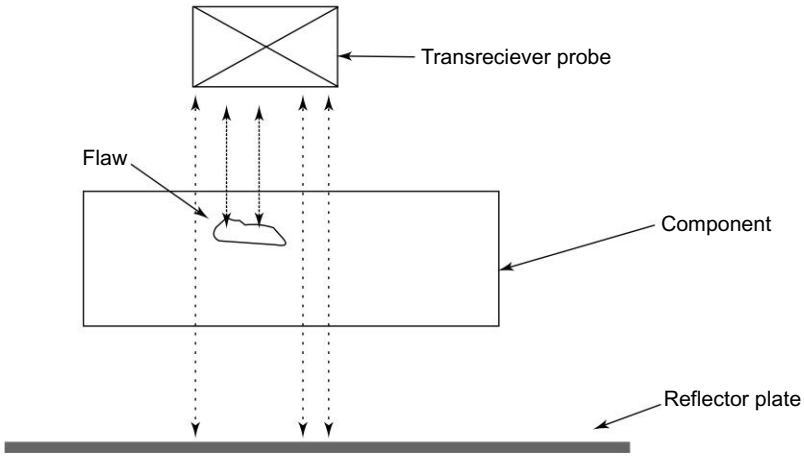


Fig. 8.4 *Reflector Plate Immersion Technique*

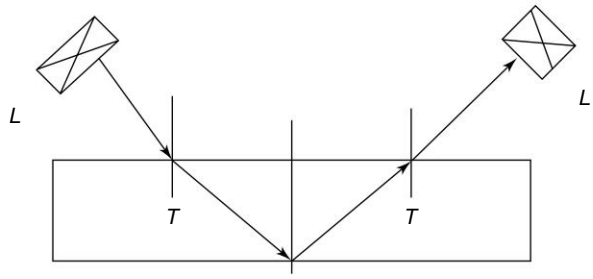


Fig. 8.5 *Shear Wave Immersion Technique*

interaction in unbounded media. These two types of waves are coupled only on the boundary of the test specimen.

Frequency spectrum analysis tools added to pulse-echo system would enable assessment of porosity (micro & macro) and the morphological factors. It is possible to obtain a quantitative NDE correlation between mechanical properties (e.g., UTS, ILSS, etc.) and microstructural features in composites, using this facility.

Potentials of ultrasonics have not been fully exploited to extract the range of information for materials and structures, it is capable of. Ultrasonic signals are modulated and modified by variation in material properties and anomalies present in the material. Each anomaly interacts with ultrasonic wave in a unique way. It is possible to extract this information from ultrasonic response through signal analysis. In this connection, data acquisition methodology and data storing on a computer for detailed analysis are important. Some of the features that can be analysed are:

- Peak amplitude and position shift of the rectified RF signal
- Area under rectified RF signal
- Rise time of the rectified RF signal
- Fall time of the rectified RF signal
- Pulse duration of RF signal

- Number of Peaks in the envelop
- Peak frequency of the frequency spectrum
- Central Frequency of the frequency band
- Energy within a specified frequency band
- Frequency area ratio of any two frequency regions
- Band width of Peak frequency (normally at–6 dB, –12 dB or –20 dB)
- Rise distance and fall distance of signal

Feature analysis can bring out such microscopic anomalies as moisture absorption, variation in dielectric properties, and help to distinguish these anomalies for better judgement. It also helps damage analysis in studying fracture mechanism, crack propagation, impact damage, etc.

Calibration Standards

All NDT results produce indirect indication of the physical state of materials and structures. These results could be in the form of data points (e.g. Attenuation parameter or thickness parameter), Output of an electronic machine (e.g. Oscilloscope trace) or Pictures (e.g. Radiograph or C-Scan map).

In order to understand the physical condition of the material/structure which produces these indications, it is necessary to fabricate standards, which simulate varied conditions of the material and structure to produce NDT indication similar to those for real life situation. These standards serve following purposes:

- Ensure consistent performance of the test system
- Check sensitivity and resolution characteristics of the system
- Evaluate size and location of defects
- Provide common basis for expressing test results.

In so far, as metallic materials are concerned universally acceptable calibration standards have been developed and adopted by NDT community. However, the situation is not the same for composites. To ensure consistent performance of the system, normal practice is to fabricate a calibration specimen, with material and lay-up same as that of the actual component. Thickness of the calibration specimen is designed to be compatible * with the thickness of test components. In practice, two types of calibration specimens with artificial defects planted at defined depths are fabricated. Artificial defects are usually made of double folded Teflon material. Details of two such calibration specimens for carbon fiber composites is given below. An example of a calibration specimen is a laminate of 104 plies (~ 0.15mm each) with repeated 45°, 135°, 0° and 90° laid up and defects introduced at different levels as indicated in Fig. 8.6.

There are 7 defects implanted in the panel, the first three are located respectively below first, second and third layers from the top surface. Similarly the last three defects are located respectively above first, second and third layers from the bottom surface. The fourth defect is located at the centre of the panel. This calibration standard is used for evaluating: (i) Entry surface resolution, (ii) Back surface resolution, (iii) Lateral resolution and (iv) Defect sensitivity.

Similarly, stepped calibration specimens can be made as indicated in Fig. 8.7. Its thickness can be taken as shown or more if the test component is of higher thickness. Ply drop area is usually taken as 1 mm thickness drop in 10 mm length. These calibration standards are used for adjusting maximum range of thickness in one scan setting.

The calibration standard for honeycomb sandwich incorporates necessary structural configuration and is also representative of damage / deficiency found during fabrication process and in service. Simulated flaws like disbond, delamination, core damage are planted in the specimen. Figure 8.8 shows such a calibration standard.

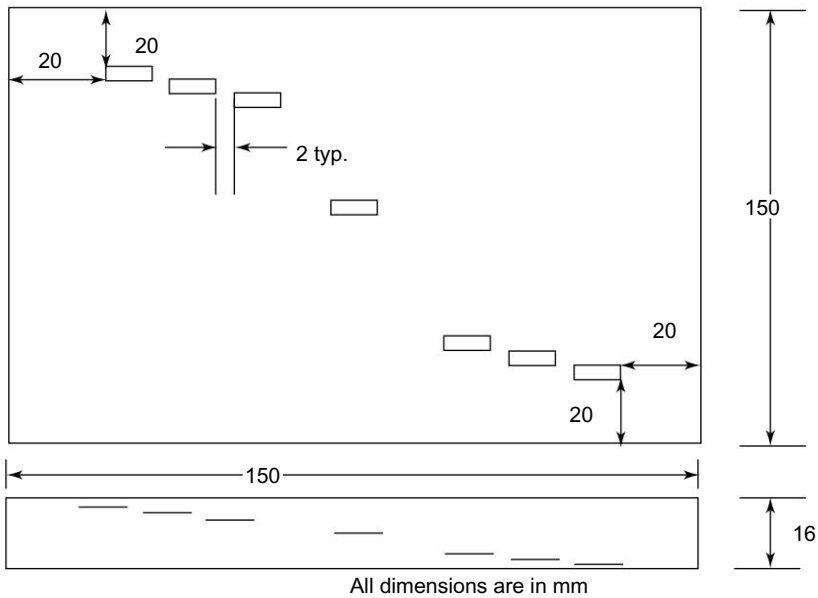


Fig. 8.6 *Flat Calibration Specimen with Implanted Defects of Size 5 × 3 mm*

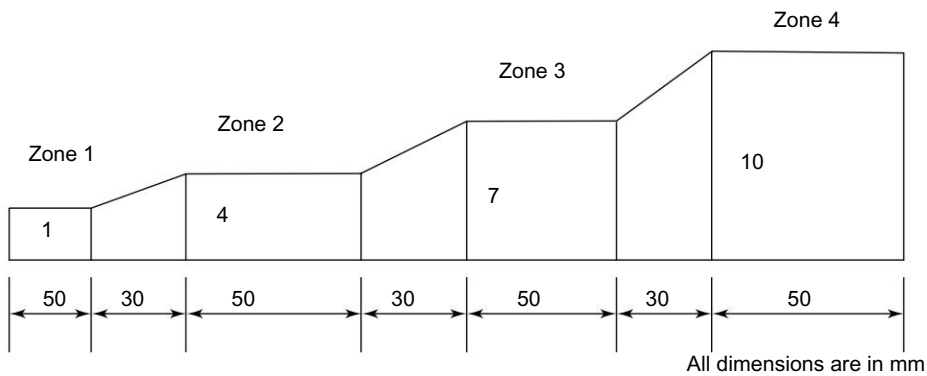


Fig. 8.7 *Stepped Specimen*

Defects introduced in the calibration standard are as indicated below. Separate calibration standards must be fabricated for different materials or a set of materials (e.g. glass fiber and carbon-fiber skins, Nomex and metallic core materials).

A. Delamination, made of double folded Teflon sheet. (Sealed all round to ensure air gap). Dimensions are compatible with acceptance limit as specified by Design.
B. Core damage. Dimensions are compatible with acceptance limits as specified by Design.
C. Inclusions (could be made of peal ply / tissue paper wrapped in a tape).
D. Edge delamination. Dimensions are similar to delamination at A.

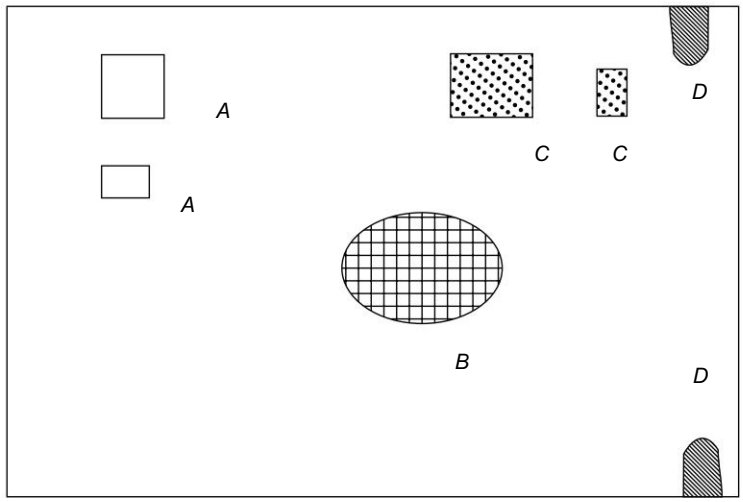


Fig. 8.8 *Honeycomb Calibration Standard*

Interpretation

Interpretation of ultrasonic test indications in addition to detection of flaws and variation in material properties, entails correlating material condition and observed test parameters/indications. This correlation may be established using fabricated samples with simulated defects and variation in material properties.

In composites, it is well known that the material and components are fabricated at the same time through a cure operation and design of lay-up. Both local and global properties are achieved during the process. Defects/deficiencies are introduced during this process.

A number of experiments have been conducted in recent years on carbon fiber reinforced composites simulating various-types of defects to get meaningful insight into the process and provide a reasonable basis for interpretation, which involves the following:

- Assessment of cure condition and material homogeneity
- Establishing nature, size, location and volume dispersion of defects
- Establish effect of defects on mechanical properties and facilitate evolution of acceptance criteria of defects and inhomogeneities

Experimental studies show that as cure operation progress ultrasonic attenuation and velocity increase and optimize at—a level, ensuring acceptable mechanical properties a Ultrasonic attenuation and velocity parameters can be used as an index of material homogeneity strength and stiffness. Figure 8.9 shows a typical photomicrograph of a cured specimen showing satisfactory homogeneity. Effect of thickness on ultrasonic specific attenuation is shown in Fig. 8.10. These observations were made at 5 MHz and 10 MHz.

Attenuation of ultrasonic energy and its time of travel through the test material is used to detect, locate and size a defect, while exact nature of the defect is established by correlating photo micrographic appearance of the defect with Attenuation and Transit Time C-scan map. It is necessary to appreciate that attenuation of ultrasonic energy during its passage through the material could be due to:

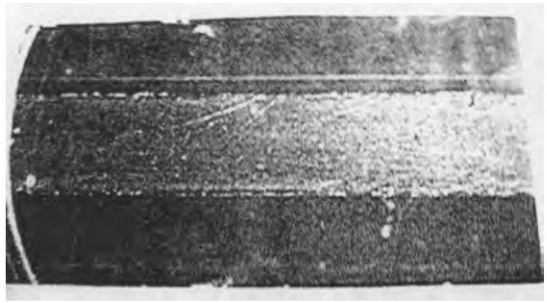


Fig. 8.9 *Typical Photomicrograph of Satisfactory Homogeneous Material Condition*

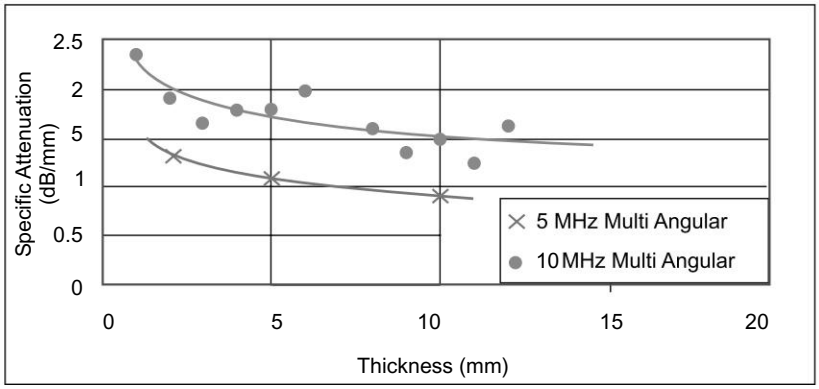


Fig. 8.10 *Effect of Thickness on Specific Attenuation of Carbon Fiber Composite*

- Surface texture
- Presence of voids/porosity
- Delamination/debond
- State of cure of resin
- Fiber volume fraction
- Condition of fiber-matrix interfaced
- Foreign inclusions

It is difficult to assess contribution of each factor, however, by maintaining uniformity of fabrication process and standardizing some parameters, it is possible to assess their relative influence on attenuation. Attenuation caused by various factors is displayed as a C-scan colour map for characterizing composite materials both in initial manufacturing environment and under conditions of field service.

In this section, various defects normally observed—in CFC (both natural and artificially implanted) are presented as revealed by C-scan.

Porosity

Porosity due to vacuum failure during manufacturing as appeared in C-scan is given Fig. 8.11.

C-scan map of laminate with porosity artificially created by spraying acetone on alternate plies of prepreg is shown in Fig. 8.12, and the photomicrograph of its section is presented in Fig. 8.13. The porosity is seen as dark spots within the section.

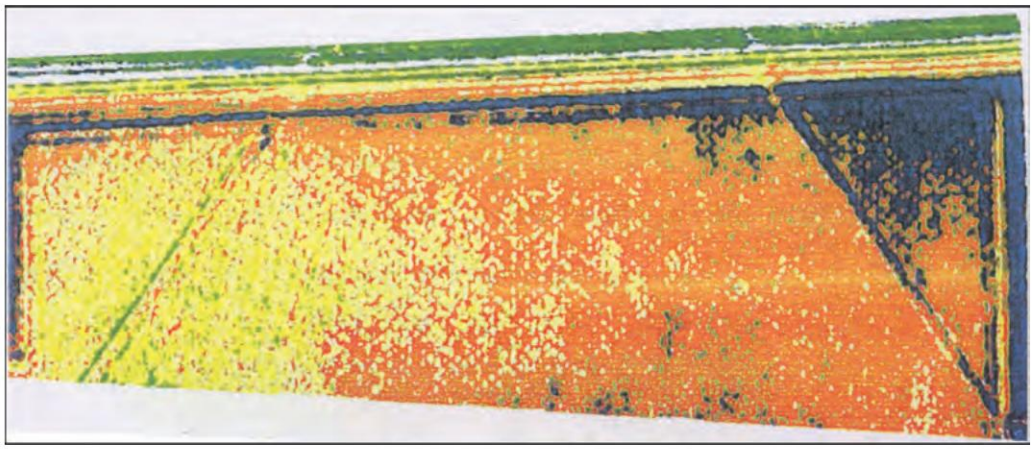


Fig. 8.11 *Porosity Due to Vacuum Failure*

Impact Damage

Under low velocity impacts, the damage may be more severe (like extensive delamination) inside the laminate than that appears at the surface. When impact damaged parts are C-scanned prior to repair, care must be taken to include entire delaminated zone, to asses the reparability of the component. The following figures shows the spread of damage due to impact damages.

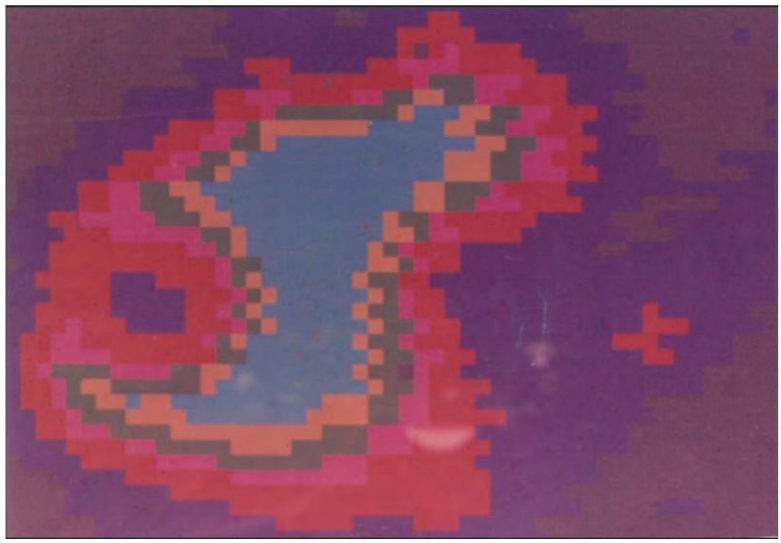


Fig. 8.12 *Low Energy Impact Due to Sharp Tool Drop*

Fig. 8.13 *Impact by 1 kg Mass Object Dropped from a Height of 2 Meters*

Figure 8.14 shows the C-scan map of delamination due to expansion of entrapped gases / volatile matter / moisture during cure. The ply gaps and the junctions of ply gaps are more prone to such detects as more volume of entrapped matter may be present there.

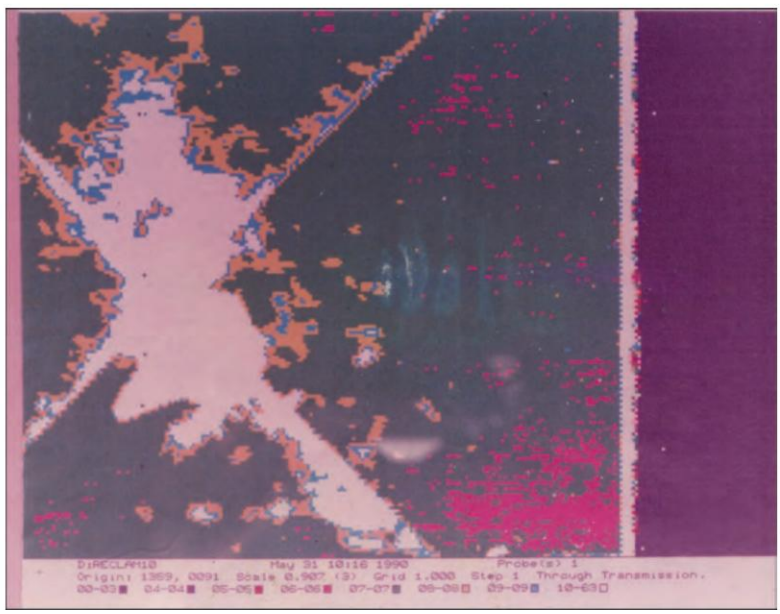


Fig. 8.14 *Delamination at the Junction of ± 45 Plies*

Figure 8.15 shows damage due to lightning strike. Such damages are characterized by excessive burning and charring in localized areas.

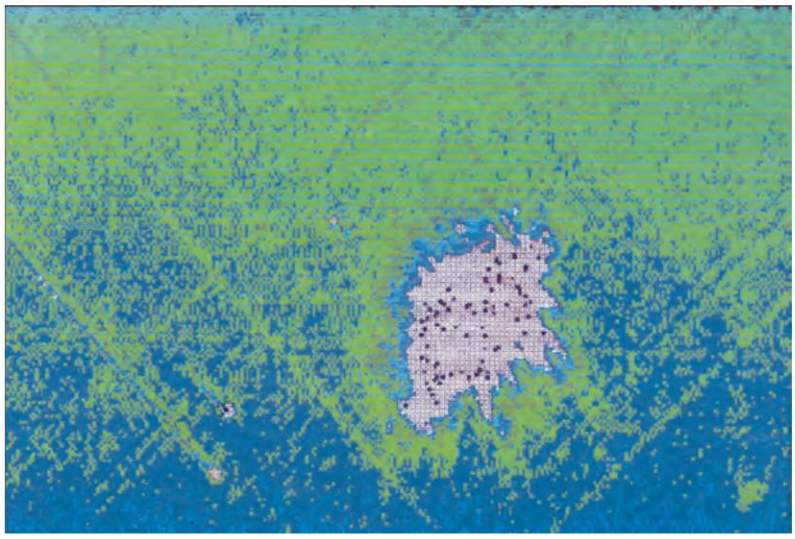


Fig. 8.15 *Damage Due to Lightning Strike*

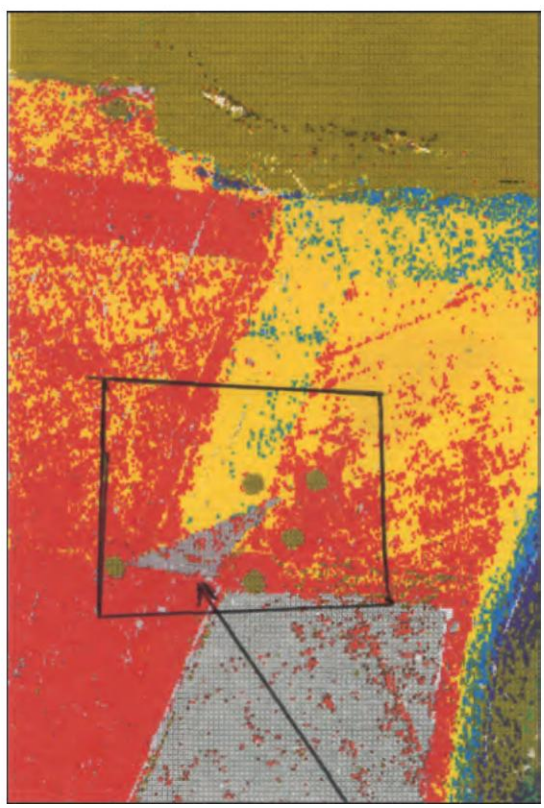


Fig. 8.16 *Inclusion in Monolithic Composite Component*

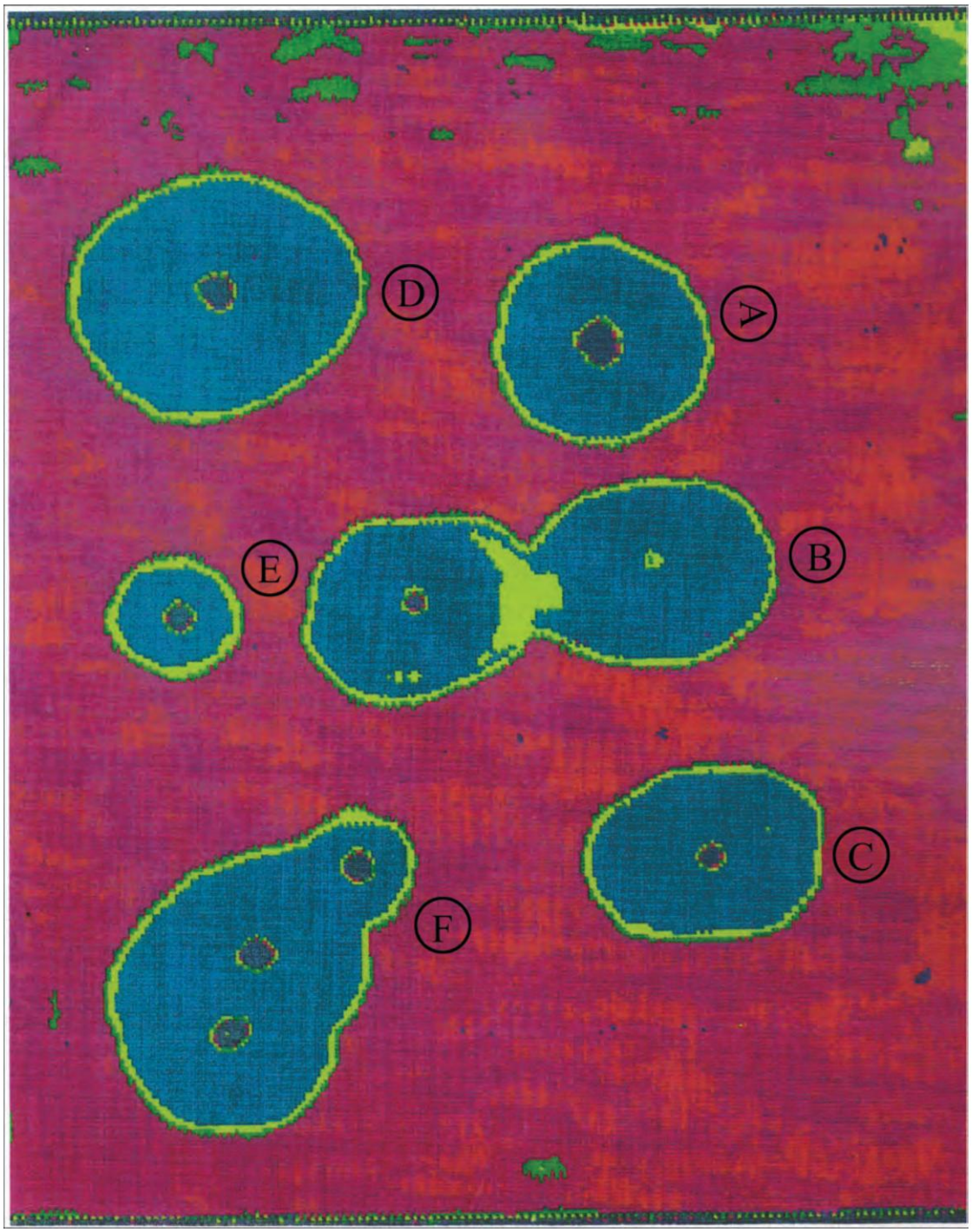
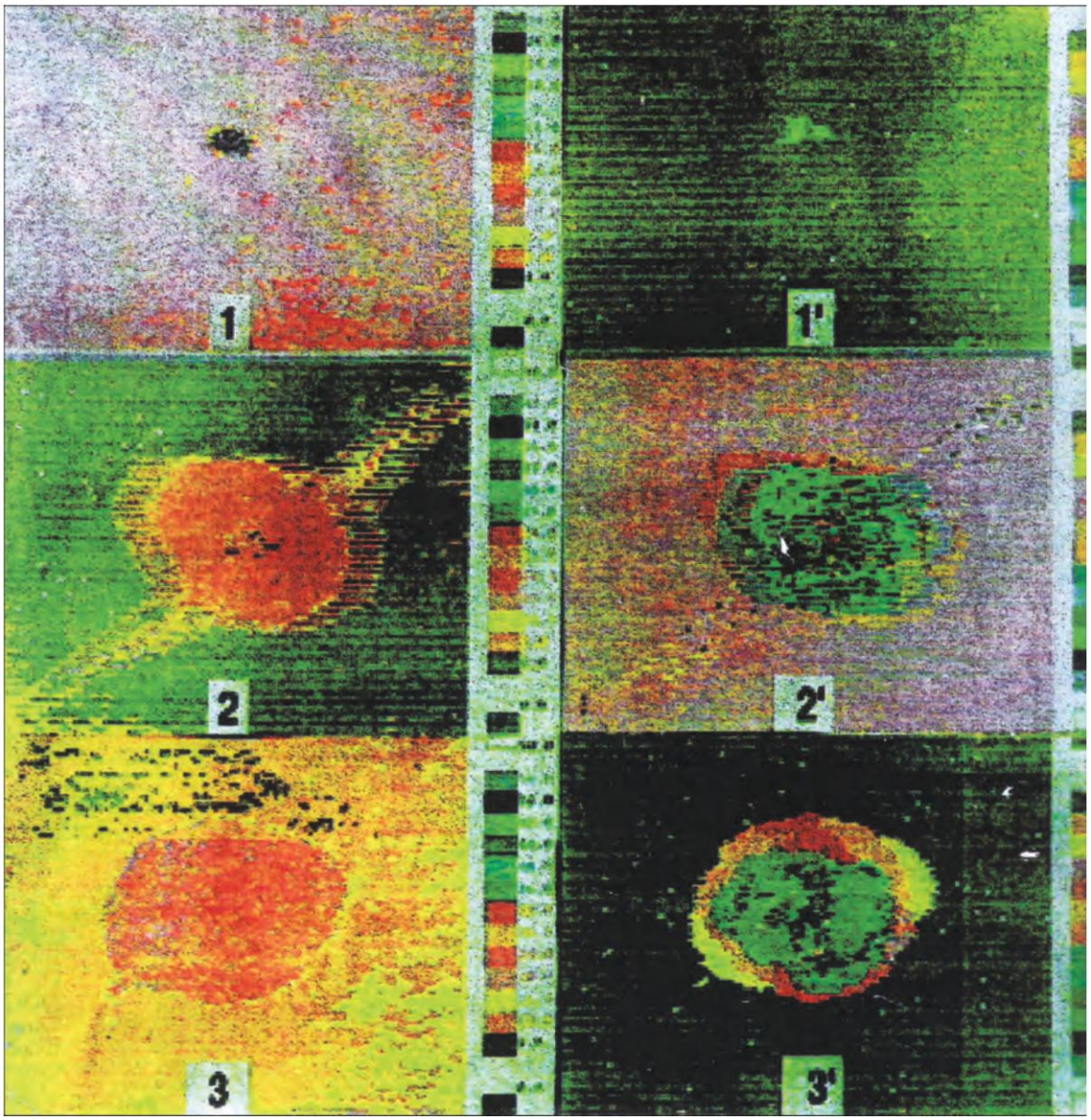


Fig. 8.17 *High Energy Impact Damage by Bullet*



Attenuation **Time of Flight**

Fig. 8.18 *Effect of Low Energy Impact Damage*
1.1′: 8 Joule Impact Damage
2.2′: 17 Joule Impact Damage
3.3′: 30 Joule Impact Damage

Low Energy Radiography

Low energy radiography is widely used for NDE of composites. Typical equipment with a beryllium window and fine focus (~ 0.4 mm × 0.4 mm), capable of operating between 10–50 KV is employed on shop floor and in field. Similar to Ultrasonics, Radiography is carried out to ensure homogeneity of material, uniformity of batch production, and to assess damage to internal components like honeycomb core, detection of voids, matrix and fibers damage, inclusions, debris, contaminants, etc.

The method however cannot detect disbond and cracks normal to the X-ray beam. Radio-opaque penetrant (e.g. terabromoethylene) may be used to improve radiographic contrast. The penetrant however has a limited application as there is always a risk of solvent residue degrading the resin. The method is used to radiograph components that are subjected to fatigue and impact damage. Fig. 8.19 gives a typical example.

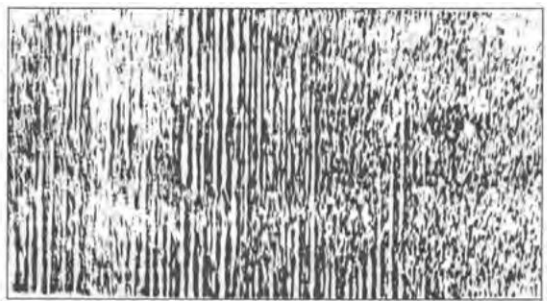


Fig. 8.19 *A Typical Example of Low Energy Radiography Using Opaque Penetrant to Show Fatigue Damage in a Composite Laminate*

For low energy radiographic examination following factors should be optimised to obtain satisfactory radiographic image.

- Energy of beam (kilovolt)
- Radiation output
- Time for which radiation impinges on the object
- Distance of the object from the source of radiation
- Spatial orientation of the test object with respect to the axis of X-ray beam
- Image recording medium
- Dimensions of the radiation source (focus)

Correct exposure parameters for a given component of known density can be determined with the help of what is known as exposure chart, prepared for specific X-ray machine, selected material and film. This chart essentially represents relationship between material thickness, beam energy (Kilovolt) and quantity of radiation (i.e., milli ampere × time of exposure). Based of this exposure chart, specific exposure technique is prepared and standardised for each component depending on its size and geometry. An exposure chart for CFC is given in Fig. 8.20.

This chart was prepared using the following:

- Step wedge specimen as shown in Fig. 8.21 for 2 mm—10 mm thickness.
- X-ray film: Indu NDT-55, Industrial X-ray film
- Focal spot size: 0.4 × 0.4 mm
- Screen filter—NIL

- X-ray film to source distance 910 mm
- Optical density for which exposure chart was made: 1.8
- Film processing: Manual for 5 mins at 26°C
- Agfa—Gaerert developer T230
- X-ray unit: Low energy, fine focus

Capability of low-energy real-time radiography has improved considerably by application of digital imaging, and it is possible to examine large structures in real time. Also low contrast in composites can be enhanced considerably. Digital imaging and low energy radiography are ideal combination for microfocus inspection. The resolution is improved by using point source of X-rays (10 – 15μm) and geometrical magnification.

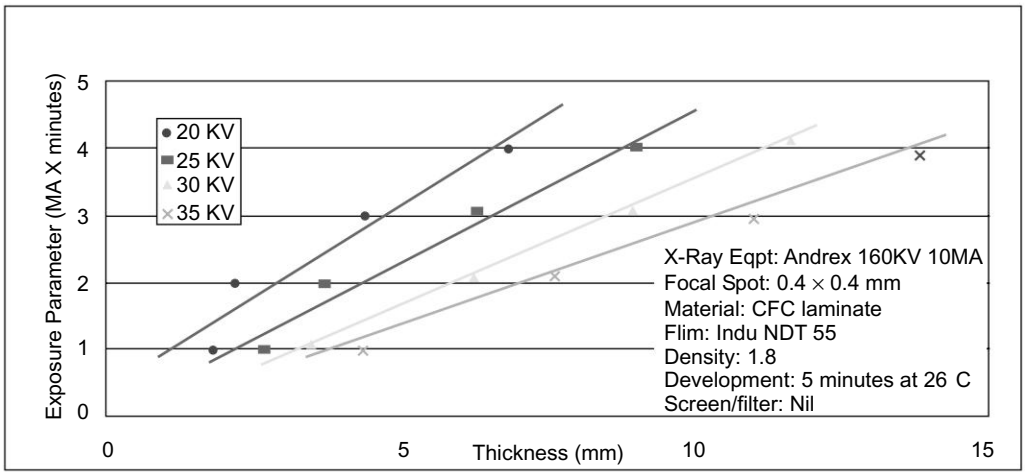


Fig. 8.20 *Exposure Chart for CFC Material*

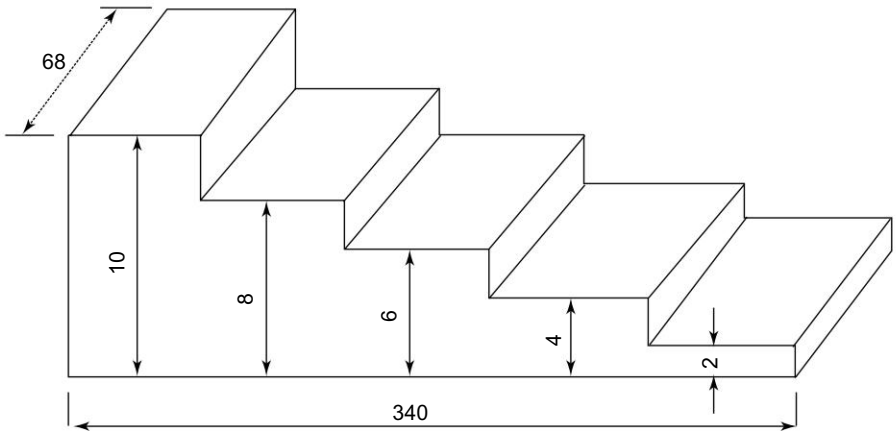


Fig. 8.21 *CFC Stepped Wedge for Preparation of Exposure Chart (all dimensions in mm)*

X-ray Computed Tomography (CT) has been applied recently to evaluate small composites component (< 500 mm). In this system, fan shaped X-ray beam is passed through the test object to get radiographic

image (X-ray attenuation) of two-dimensional slices of the object, without interference from overlying or underlying areas. Figure 8.22 illustrates this. The method is highly sensitive to small differences (< 1%) in material density.

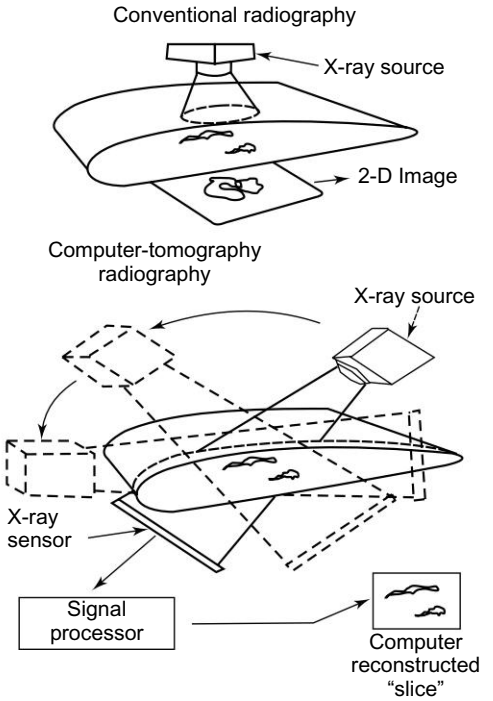


Fig. 8.22 *X- Ray Computer Tomography*

All NDT indications are interpreted by qualified persons with understanding of the material, process, adequacy of the technique and acceptance criteria. Interpretation is based on appropriate reference standards. Documents used are exposure charts, reference standards containing various sizes of simulated defects, standard on specific technique defining exposure parameters, sensitivity, film processing, density, range for film, area/volume coverage, etc.

Other Methods of NDT for Composites

Other methods that are used with varying degrees of success for NDE of composite are described below:

Visual

Visual examination of surface is the most commonly used for detecting crazing, cracks, scratches, nicks, blisters, pitting, resin rich and resin starved areas, discolouration, wrinkles, open voids and delamination. Visual aids such as intense light or magnifying glasses are used to increase detection capability. Reflected light is used to observe surface irregularities and other defects. Transmitted light is often used for glass fiber-reinforced composites to reveal defects within the material. Any indentation of the surface without visible damage to the fibers, is analysed by other NDT methods before acceptance.

Coin Tap Test

Coin tap tests (also called sonic test) i.e. tapping a structure with a coin or other metallic object is a common technique for qualitative detection of gross conditions, such as cracks and delaminations. A well defined ringing sound is indicative of well bonded structure. A dull or thud indicates delamination or relatively a large void / delamination area. The method is used as a preliminary check on shop floor or in the field.

Fockker Bond Tester

This is an ultrasonic resonance type instrument, which uses Piezoelectric crystal, vibrating at ultrasonic frequency, as sensing element. When the transducer is placed in contact with the material under test, its vibration is influenced by the characteristic of the material (e.g. stiffness, damping characteristics). A voltmeter indicates the amount of damping of the transducer vibration and CRT indicates the shift in resonance frequency. The tester is calibrated with bonded specimen of known quality. The quality of bond of the test object is determined from the resonance frequency shift or the damping of the peak amplitude.

Thermography

This technique enables contours of equal temperature - isotherms to be mapped over a surface. Its application is based on the assumption that defects, inhomogeneities or any other undesirable condition of test object will be evidenced as local hot or cold spots in isothermal mapping. Application of the technique requires:

- Arrangement for heating or cooling surface of the test object
- Assessment of the areal temperature distribution surface of the test object
- Interpretation of the results in accordance with established physical principles. The system is a complementary tool of NDT and has a definite role as a non-contact NDT method for detection and evaluation of defects, moisture entrapment and service induced defects during service. The system is also usable on shop floor to assess large composite components, immediately after removal from autoclave. Result of examination of composite laminate containing artificial defects is shown at Fig. 8.23.

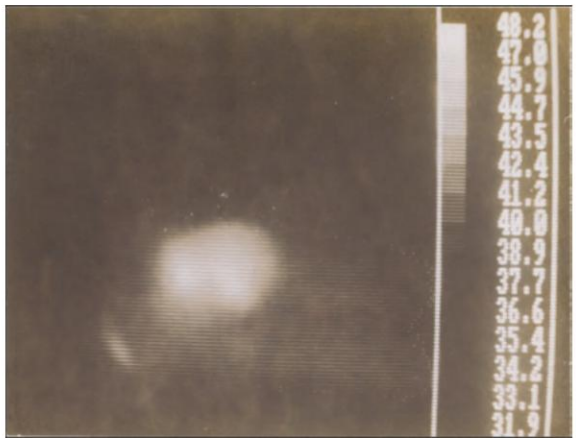


Fig. 8.23 *Entrapped Air between Plies*

Acoustic Emission Testing

Stress waves produced by sudden movement are designated as acoustic emission. The sources of acoustic emission are defect related deformation process, such as crack growth and plastic deformation. The method has found application to evaluate metals and composites. A few application examples include, study of fracture specimens, pressure vessels, composite components and fluid systems. The method measures number, intensity, amplitude and energy distribution of acoustic pulses and evaluates build up of damage during loading of a structure, crack formation, failure of structural elements and adhesive bond in composites.

Eddy Current Testing

The electrical conductivity of carbon fiber composite shows significant impedance change. Nominal conductivity of carbon fiber composites ranges from 5000-2000 μΩ/ cm. The conductivity depends on fiber type, density and weaving pattern. Eddy current test is carried out in the frequency range of 12–50 MHz to detect surface damage in carbon-fiber composites resulting from fiber damage and density variation.

Robot based C-scan eddy current testing has been used to inspect skin of Boeing 737 aircraft. The system can detect defects in second and third layer of the skin and often in the ribs to which the skin is fixed.

8.2 DEFECTS IN COMPOSITES AND THEIR EFFECT

Range of defects observed during fabrication and service is shown in Table 8.1.

Table 8.1 *Defects Induced During Fabrication and Service*

During Fabrication and Service	*During Service*	
	Service/Loading condition	*Corresponding Defects*
Voids, porosity, delamination, broken fibers, inclusions, insufficient curing, missing piles, impact damage during handling crazing-cracks.	Fatigue	Matrix cracking, crazing, fiber break and delamination
	Impact	Delamination, fiber damage
	Lightning strike	Debond between fiber and matrix, delamination, burning and puncturing.
	Environmental	Matrix plasticisation, debond, irradiation effects
	deterioration	
	Erosion	Reduction in thickness

Magnitude of defects, discontinuities and inhomogeneities that occur in composite structures vary depending on facilities and skills available during fabrication. These defects tend to reduce mechanical properties and structural integrity.

Following tables give a summary of defects, NDT methods and their effect.

Defect in Monolithic Structures

Defect	*Description*	*NDT method*	*Effect of Defects/Remarks*
Porosity	Closely spaced small voids	Ultrasonics	Deterioration in mechanical properties like compression strength and ILSS
Delamination	Separation of plies in a laminate due to internal stresses or in sufficient pressure during cure	Ultrasonics	Deterioration in mechanical properties, more critical in compressive stress field.
Inclusions	Foreign object (usually in sheet form)	Ultrasonics	This leads to local reduction of compressive strength and Inter laminar shear strength.
Blistering	Air pocket and heat during cure cycle leading to lack of bond between plies.	Ultrasonic s	Depending on location, the effect is similar to that of delamination
Resin rich area,	Resin build up caused by resin flow during cure.	Ultrasonics, Low energy radiography	It has local influence on transfer of shear stresses.
Resin starved area	Areas not uniformly coated with sufficient resin.	Ultrasonics, Low energy radiography	Deterioration in mechanical properties.
Surface fiber break	Broken fiber yarn's at production stage.	Ultrasonics, High frequency Eddy current, visual	Deterioration in mechanical properties.
Fiber/wrinkle/ kinks	Raised fold of fibers, produced by resin flow, often observed at angled sections	Visual	These are likely to produce micro cracking and microbuckling.
Surface scratches	These can have variety of forms but essentially break fiber in the outer laminae.	Visual	Scratches reduce the tensile strength in proportion to the number of 0° plies cut. There is a possibility that such scratches generate delamination and low buckling strength.
Translaminar cracks	Cracks running in the matrix or fiber to matrix interface, parallel to the fibers	Ultrasonics	Such cracks can lead to serious delamination damage. Initially translaminar cracks can be visualised as increased ultrasonic specific attenuation.

(*Contd.*)

(*Table Contd*)

Defect	*Description*	*NDT Method*	*Effect of Defects/Remarks*
Bearing damage	These are local damages which include fiber fracture	Ultrasonics, Eddy current, Visual	It results in reduction of joint stiffness. If such damages occur at a number of fastener holes in one area then overall stiffness will be affected.
Matrix crazing	Not encountered with epoxy resins but possible with some organic matrix.	Radio opaque radiography	Loss of ILSS.
Impact Damage	Extensive internal damage in visible at the surfaces.	Ultrasonics	Drastic reduction in compression strength.
Battle damage, bird strike	Puncturing of the surface accompanied by severe fiber damage and delaminations	Visual, ultrasonics	Damages in visible and non-visible region. They are to be evaluated for their extent of damage, with a view to repair it.
Severe lightning strike	Puncturing of the surface, fiber damage and delaminations and local charring.	Visual, ultrasonics	Deterioration of mechanical properties locally at the damaged area.

Defect in Honeycomb Structures

Defect	*Description*	*NDT Method*	*Effect of Defects/Remarks*
Lack of integrity of bond line (inadequate bond strength, disbonding), and bond line thickness variation.	Lack of adhesive in bonded composites due to: i. internal stresses ii. lack of curing iii. improper surface preparation	Radiography and Through Transmission Ultrasonics	No satisfactory NDT method is available to know bond strength. The defect leads to loss of stiffness and strength and local buckling depending on the size of the defect. Weak bonds may go undetected at the manufacturing stage
Non-uniform adhesive thickness	Adhesive variability	Radiography	May lead to local buckling
Damaged cells	Crushed or distorted core, and honeycomb cell tear out	Radiography, Through Transmission Ultrasonics	Affects the rigidity of the structure and leads to poor shear transmission.

(*Contd.*)

(*Table Contd*)

Defect	*Description*	*NDT Method*	*Effect of Defects/Remarks*
Lack of filleting between honeycomb core and face sheet	Non-uniform fillet formation between foaming adhesive and core splice.	Radiography, Through Transmission Ultrasonics	Fatigue resistance is reduced.
Lack of foaming adhesive core to core splice	Non-uniform fillet formation between foaming adhesive and core splice.	Radiography, Through Transmission Ultrasonics	Strength reduced and it may be considered a serious defect.
Variation in glue line thickness	Non-uniform thickness of bending	Radiography, Ultrasonics	Reduction in shear strength.
Voids/ moisture in core	Small voids	Radiography, Ultrasonics	Effect similar to debond
Inclusions	Foreign inclusions in sheet form	Radiography, Ultrasonics	Local reduction in compressive strength and ILSS.
Impact damage/ denting	Surface depression	Visual	Loss of contour smoothness
Shrinkage of core potting/ filling.	Partial junction, not completely filled with foam adhesive	Radiography, Ultrasonics	Deformation of core and wrinkles
Film adhesive shrinkage	Folded film adhesive in the splice	Radiography, Ultrasonics	Uneven shear strength.
Gap in core-splice	Gap in the junction of two honeycomb core pieces	Radiography, Ultrasonics	Loss of stiffness and strength.

Moisture Absorption

It is known that ingress of moisture can affect mechanical and electrical properties of composites. Moisture is taken up chemically in the matrix i.e. it is molecularly bound and not present as free moisture. This form of moisture lowers Glass Transition temperature and particularly affects compression strength However, micro defects present in the material cause water to be absorbed as free moisture. Vaporization of free moisture due to temperature raise (for example during passage of lightning current) may cause local explosion. NDT assessment of moisture ingress in either form is essential.

Effect of Porosity

Among the defects that significantly influence mechanical properties of fiber reinforced composites is porosity. Porosity may be introduced due to inadequate pressure on the laminate during cure, vacuum bag leakage or lack of resin due to its out flow (as happens in time expired material).

Effect of Delamination

Presence of delamination leads to reduction in shear strength, buckling/compressing strength. Tensile strength is not effected till some load bearing fiber breaks. The important point to be noted is the significance of delamination or any other defect varies according to its location with respect to stress field.

Effect of Notches and Surface Scratches

Notches and scratches often occur during handling and assembly of components. This leads to local variation in strength and stiffness. There is also a possibility of such notches initiating delamination damage , resulting in low compressive strength. Such defects can be detected and assessed visually or by eddy current test. Ultrasonic method may be employed to detect presence of delamination accompanied by scratches.

Effect of Thickness Variation Due to Ply Omission

Inadvertent omission of plies may occur during lay up of large components due to negligence. This leads to local variation in strength and stiffness in addition to reduced thickness, depending on the number of plies missing their orientation. Ultrasonic C-Scan transit time map provides a reliable method for assessing variation in local thickness. A correlation between actual thickness and ultrasonically measured thickness is shown in figure below, in carbon fiber reinforced composite.

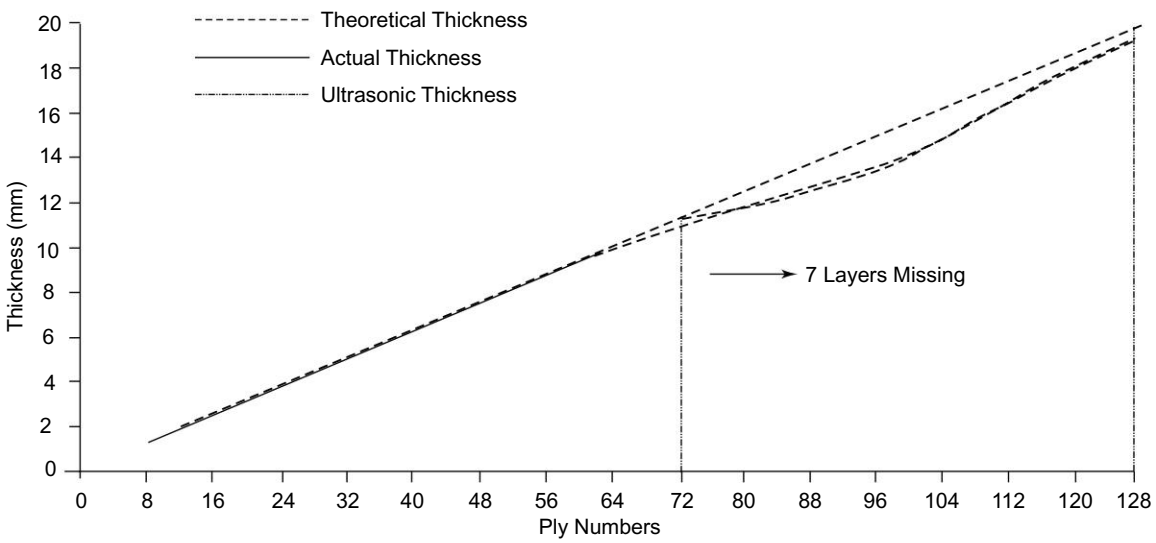


Fig. 8.24 *Effectiveness of Ultrasonic in Evaluating Thickness Variation*

8.3 STRUCTURAL SIGNIFICANCE OF DEFECTS AND ACCEPTANCE CRITERIA

Engineering structures are designed to sustain ultimate design loads. Normally, a factor of safety is allowed to cover variation in geometrical factors, bearing lads and ageing. The allowable factor, however does not contain any provision for problems of fabrication and processing or likely impact damage and environmental deterioration .The significance of defects, dimensional variation or inhomogenities owing to manufacturing processes, service loads or environmental constraints varies according to its location with respect to stress field. No generic information is available to assess. Interaction of defects with structural features. General practice is to generate empirical data to evaluate effect of commonly occurring defects on design stipulated properties. This approach has obvious limitations.

It is observed that majority of failures in composites are due to out of plane loads which are unexpected and un-recognized. To appreciated interaction of defects with structural features, one has to keep in mind the following:

- Matrix sensitive failure modes are driven by bi-directional and out of plane loads, Environmental effects and cyclic loading
- Impact effect depends on lay up sequence, thickness and type of support provided to the structure. Small support span in the region of impact promotes interlaminar shear failure, while large support span, thinner laminates are likely to produce flexural failure

In absence of design philosophy on structural significance of defects and non-availability of a practical methodology for its assessment normal practice is to generate an empirical "defect-property" data for flat specimen and assume that a defect is significant if it reduces design stipulated property. However, one has also to consider factors like limitation of inspection equipment and available expertise.

Further, severe defects reduce strength and endurance of a structure, while minor localized defects are of little significance. The attention is given to probability of occurrence, location and spread of defects/damages and repair needs. For our purpose, we may define a structurally significant defect as that which will reduce design stipulated properties within the expected service life of the structure. Currently a design allowable limit of approximately 4000 micro-strains, as a guide line for accommodating defects and damages in areas subjected to uniform in-plane stresses, is considered acceptable. In areas of non uniform stresses, the effect varies according to its location in a given stress field. This requires generation of specific data for a given situation.

Based on experience, it appears that voids often occur at angled sections, porosity occurs in region of ply drop, machining and assembly damage occur at cut-outs and bolted joints. Rough handling usually results in damage to free edges. Assembly and service induced damages due to local impact may occur at any point. The regions around access panels and attachment points are prone to low velocity impact.

Finally, it is necessary that materials/components/assemblies are characterized in terms of specific properties that designers may relate to design parameters to certify it as meeting required characteristics/ functional properties.

8.4 REPAIR OF COMPOSITES AND NDE

Composite structures may suffer damage at any stage of its life cycle: Production, Transportation, Assembly or Service and require repair. The first step for repair is to identify the nature and extent of damage. Generally the damage is classified as:

- Negligible damage
- Repairable damage
- Sever damage
- Non repairable damage

The damaged composite part could be solid laminate/monolithic or sandwich. As far as possible repair is carried out with identical reinforcement and core material. Often fast curing resins are used to save time. Sever damage is repaired by manufacturing agency, if economical.

The objective of repair is to:

- Ensure freedom from harmful defects and inhomogenities
- Restore strength and stiffness
- Achieve thickness variation within allowable limits
- Restore surface contour

The repair is intended to restore load-bearing capability of the structure making the area similar to the original design. But departure is often permitted in low stress zones. Repair is carried out by riveted or adhesive bonded doublers/reinforcements. If the damage extends through the entire thickness of the laminate, repair is carried out in following steps:

- Back side of the laminate is supported by a back up plate
- Removal of damaged area
- Grinding of continuous or stepped overlaps
- Cleaning of ground surfaces
- Surface treatment with low viscosity resin
- Lay up of sufficient layers to match the original thickness
- Curing under vacuum at proper temperature and pressure
- Grinding, polishing and replacement of surface coating

Damage in sandwich panels can be on face sheet or extend through one of the face sheets affecting the core material or loss of both face sheets and the core. Face sheets are repaired in the same manner as laminates. The damaged core is repaired with a resin either by stabilizing or by fully removing and replacing it. In case of core replacement good adhesion is ensured to its neighboring core material and to both sheets.

The role of NDE in pre repair stage is to determine the nature of damage and demarcate extension of damage. During the process of material removal and preparation for repair, NDE provides information on satisfactory removal of defective areas. In post repair stage, NDE ensures freedom from harmful defects and in-homogeneities. Further, restoration of thickness, strength and stiffness is validated through NDE methods. Ultrasonic pulse-echo methods with attenuation and transit time mapping facilities are used for this purpose. Defects usually found after repair are—porosity, poor filleting and non-uniform bond line thickness of sandwich. Thickness and contour variation often occur. Repaired honeycomb structures are evaluated using through Transmission Ultrasonic or Radiographic methods.

All repair activities need to be documented, giving design requirement, repair procedure, evaluation and acceptance criteria.

Ultrasonic pulse-echo methods with attenuation and transit time mapping facilities are used for this purpose. Defects normally found after repair are—porosity, delamination. poor filleting and non-uniform bond line thickness. Thickness and contour variations are often observed. Repaired honeycomb structures are evaluated using 'Through Transmission' Ultrasonic or Radiographic methods. All repair activities

need to be documented giving design requirements, repair procedures, evaluation and acceptance criteria and specific NDT methods applicable in each case.

8.5 Application of Composites

Fiber-reinforced composites find wide range of applications in various industries. Table gives an example of their applications.

Table 8.2 *Applications of Composites*

Industry	*Application*
Chemical	Corrosion resistant pipes, Tanks, Pressure vessels, Pocess equipment
Electrical	Swith-gear components, Electro mechanical hardware
Transport	Body parts for cars (Drive shaft, bumpers), Cooling fans, engine covers for trucks and buses, seats
Railways	Window assemblies, bathroom components, Electrical junction boxes, seats rail-insulators, rail joint systems
Electronics	Copper clad laminates, computer housing, connectors
Marine	Work boats, fishing boats & trawlers, pleasure boats, buoys
Building	Roofing sheets, domes, furniture, cladding panels, modular housing, sanitary fittings, partition boards and doors
Protective equipment	Helmet, welding masks, Armour
Aerospace and Defence	Aircraft parts, rocket motors and castings, missile bodies, launchers, naval boats, torpedo castings, high altitude huts, and heat shields
Sports	Golf clubs, tennis racquets, vault poles, skiing boards
Agriculture	Irrigation piping, sprinklers
Miscellaneous application	Pipes for deep sea mining, human implants, aids for physically handicapped

9 Industrial Applications of NDE

9.1 Span of NDE Activities

NDE is widely used in industries (Figure 9.1 shows span of NDE activities) or for the verification of design quality, certification of manufactured products, assessment of product degradation and effective repair or replacement during service. NDE has also been a valuable tool in risk assessment based on experience. This chapter brings out the effective support of NDE in appreciating problems related to material behavior, operation, maintenance and repair of components and systems, and in ensuring operational safety and reliability.

9.2 Railways

A number of railway components and assemblies are tested and evaluated using NDT methodologies during manufacture for freedom from unacceptable defects and anomalies. The major components subjected to various NDE methods are: wheels, axles, bearings, rails, welded rail joints, bridges, etc. Figure 9.2 shows some of these components.

Wheels are fixed to an axle. The part of the wheel sitting on the rails is called the tyre.

The test methods commonly used during fabrication are visual examination, the magnetic particle test, the liquid penetrant test, ultrasonics and radiography. These methods are used to detect and evaluate surface, sub-surface and internal defects.

During service, NDE methods are used to monitor components to ensure their continued usage. However, it is essential to take account of the fact that these components are subjected to extreme conditions of service loads, frictional wear, high temperature and corrosive environment. These factors lead to the initiation of cracks, breakage of components, gauge spreading, unacceptable residual stresses and deterioration of material. These damages and deterioration contribute to accidents, derailments, and the failure of individual components/assemblies. To minimize the occurrence of accidents or the

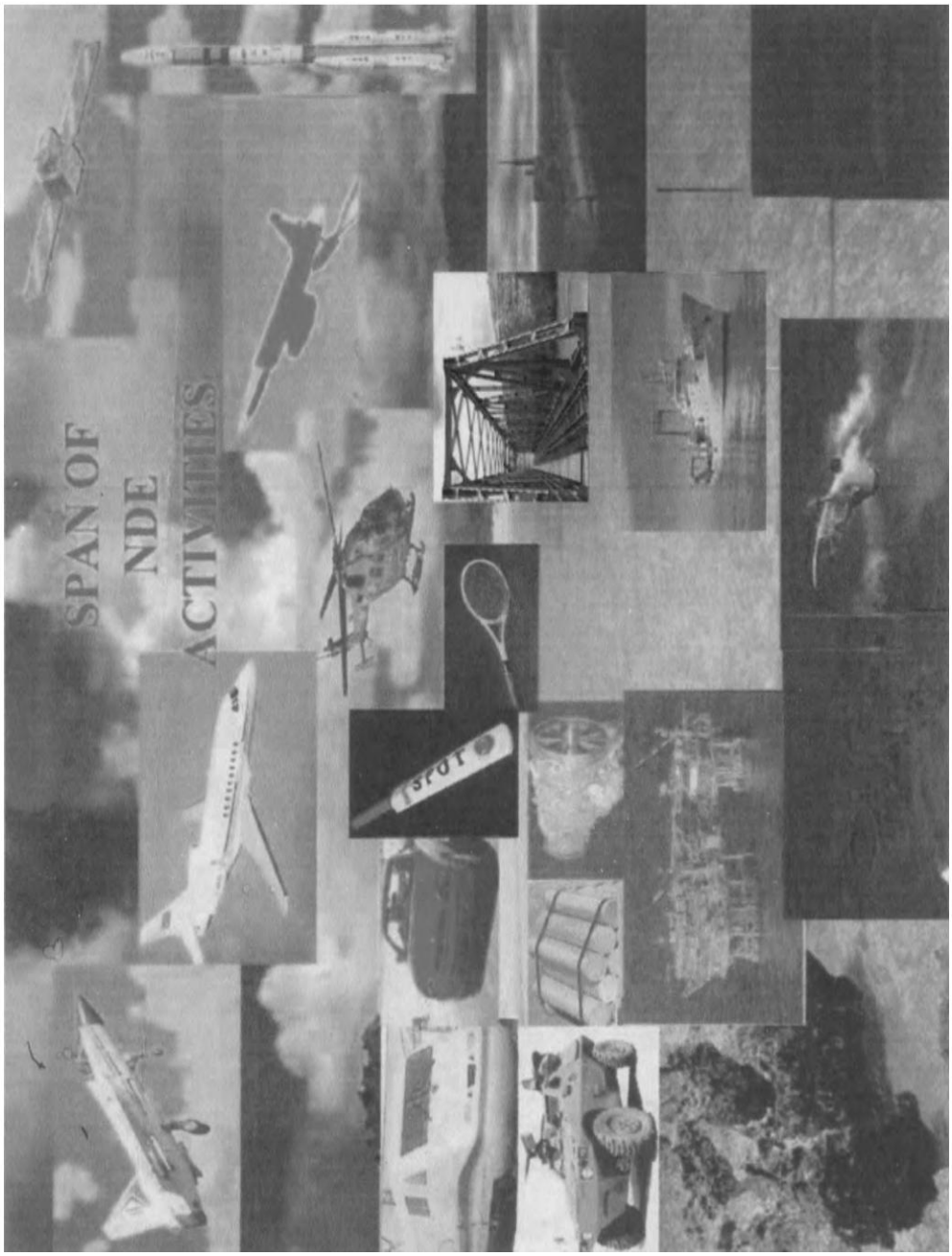


Fig. 9.1 *Span of NDE Activities*

deterioration of components and assemblies beyond acceptance limits components and assemblies are subjected to periodic NDE checks and records are maintained, keeping in view the traceability requirements.

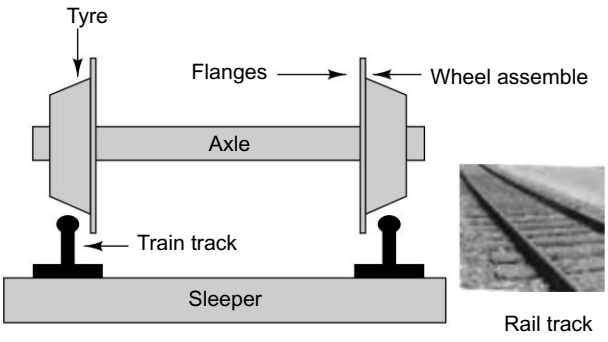


Fig. 9.2 *Assembly of Wheels, Axle and Train Track*

Fig. 9.3 *A Railway Bridge*

Usually, specific test and evaluation techniques are developed for each situation, depending on the part configuration, assembly condition, test environment and sensitivity required by acceptance standards. In case acceptance standards are not available, sufficient data needs to be generated in coordination with design and maintenance agencies. Currently, ultrasonic methods in pulse-echo mode constitute the most widely used NDE method, in the frequency range of 2-5 MHz for the detection, location and evaluation of defects. Both manual and automatic test systems are used worldwide. Ultrasonic velocity gives a good idea of material deterioration and unacceptable residual stresses.

Other methods are used depending on specific requirements.

Apart from components, railway bridges are essential for continuous movement across water-ways and many other obstacles. The role of NDE in this regard, is to support the maintenance of bridges in service. Conventional as well as advanced methods like acoustic emission are used to detect and monitor corrosion and cracks in critical members of bridges. For the repair and replacement of members, NDE is used to ensure effective repair.

Further, an area of concern is health monitoring of railway tracks to avoid/ reduce derailments and accidents as failure could be very expensive in terms of life and property. Apart from visual and ultrasonic inspection, instrumented hammer excitation is used as a tool for evaluation and monitoring railway track structure. In this method, signal analysis is used to examine vibration response of the structure to the impact excitation. The impact excitation is converted in to frequency response function and parameters like frequency, damping and mode shapes are extracted for health monitoring.

9.3 Nuclear, Non-nuclear and Chemical Industries

Welding is the major manufacturing process for various equipment and assemblies in nuclear, non-nuclear and chemical industries. The major equipment and assemblies fabricated by welding are pressure vessels, boilers, heat exchangers, storage tanks and industrial and transmission piping.

The internationally accepted codes and standards followed in the fabrication of these components are: ASME Code, Indian Boiler regulations, Indian Standard 2825, British standard 1515, TEM Standard for heat exchangers, American Petroleum Institute Code API-1, API-62, Indian Standard Code 15-803 and Japan Industrial Standards.

The materials used to fabricate these components are comprised of low carbon steel, low alloy steels, stainless steels, ferritic stainless steel, nickel base alloys, copper-nickel alloys, titanium, admiralty brass, etc. The commonly used processes of welding are TIG and MIG.

The role of NDE during fabrication is to ensure the structural integrity of components. NDE methods ensure the acceptability of butt and fillet welds for satisfactory root penetration; proper fusion in fillet welds for joint efficiency and freedom from unacceptable cavities, porosity, inclusions, cracks and mechanical damages.

During the fabrication of pressure vessels, NDE is required to examine and evaluate longitudinal, circular and nozzle welds. Radiography, magnetic particle, liquid penetrant and ultrasonic methods are commonly used. Test techniques and acceptance standards are prepared and documented based on the mutual agreement between the manufacturers and users of the product. The documents are prepared based on universally accepted codes, standards and specifications.

Heat exchangers form vital components in a large number of process plants. These are examined during fabrication to control the process of fabrication and during usage to prevent failure and initiate replacement. Usually, the following techniques are used to examine tubes: eddy current, ultrasonics, helium leak test and visual examination.

Bobbin type eddy current probes are inserted into the tube through a probe drive system. Multi-frequency test modes are used to detect local corrosion, erosion and cracks and also to locate foreign materials. Tubes of magnetic materials are tested by eddy current using saturation techniques.

Ultrasonic rotatory inspection using the pulse-echo technique is used to examine the circumference of the tube wall. The tube wall thickness is assessed by this technique. The ultrasonic P-scan technique is used to examine tube-to-sheet welds from inside. The method is used to detect the lack of fusion, pores and inclusions.

The helium leak test is used to detect leaks for the entire heat exchanger or for a single tube and is sensitive to all types of leaks. The inner surface of the tube is assessed by visual examination with the help of cameras and video endoscopes. The camera or endoscope is inserted into the tube and examination is performed after the camera or endoscope is withdrawn. Liquid penetrant methods are also used to assess the presence of corrosion in the tube sheet.

Table 9.1 gives a brief idea of defects introduced in components during fabrication and service and the most commonly used NDE methods for their detection and evaluation.

These plants require the application of NDE for both curative as well as preventive maintenance. Curative maintenance is carried out by the detection of existing defects and the progress of component degradation. The data generated at this stage helps one to decide whether to initiate repair or replacement or to leave the components as is.

Preventive maintenance is carried out during the shutdown of the facility. Conventional NDE methods are used, keeping in mind the requirements of codes, standards and specifications.

TABLE 9.1 *Defects observed during fabrication and the service and the NDE methods used*

Components	*Defects*	*Commonly Used NDE Methods*
Pressure vessels and boilers	Lack of penetration, lack of fusion, cavities, cracks, porosity, corrosion, pitting, change in wall thickness, hydrogen embrittlement, stress corrosion, thermal fatigue crack and creep deterioration	Radiography, ultrasonics, magnetic particle, liquid penetrant and visual check
Heat exchangers	General corrosion/erosion, pitting, support plate fretting, stress corrosion, cracking and mechanical damage	Eddy current (single and multi-frequency test) ultrasonics (IRIS) examination, ultrasonic P-Scan, helium leak test, visual examination, magnetic flux leakage test
Storage tanks (above ground and under-ground build tanks, including large tanks used in petrochemical industries)	Corrosion, wall thickness change and welding defects	Radiography, ultrasonics, visual checks, magnetic flux leakage check, remote video camera mounted on robotic arm. Robotic systems are used to perform ultrasonic weld inspections, especially for large tanks in petrochemical industries
Pipes (metallic and composite)	Inter-granular stress corrosion, pitting, microbiologically initiated cracks, erosion	Ultrasonics for surface breaking cracks, radiography, acoustic emission, visual checks

9.4 Aircraft and Aerospace Industries

The role of NDE in aircraft and aerospace industries is considerably influenced by the following features of design and application:

- The selection of materials and manufacturing processes is dictated by design requirements of high specific strength and stiffness. This means that components have to be light weight and highly loaded. Tolerance for design stipulated properties and the dimensions, size and distribution of defects is very stringent
- Aircraft and aero-engine components operate under cyclic loading and are prone to fatigue cracking. Further, components are subjected to a hostile environment of corrosion, erosion, extreme temperature variation and lightning strikes
- Increasing usage of composites, foam honeycomb and sandwich structure, particularly for aircraft and aerospace components

In view of these features, every component needs to be carefully examined and certified before assembly into systems. During service, aircraft and aeroengine components are monitored periodically for continued serviceability throughout their useful lives.

The selection of NDE techniques depends on the test environment, assembly condition and the required deflect sensitivity. Test techniques are required to detect, locate and evaluate the defect/damage before it becomes a major problem.

Coin-tap, visual examination, radiography, ultrasonics, magnetic particle, liquid penetrant and eddy current tests are extensively used to examine and evaluate surface and internal defects. In addition to these methods, acoustic emission, infrared thermography, high frequency eddy current, laser sherography and holography is also used. In recent years, a number of state-of-the-art technologies have been developed for detection, visualization, automatic dimensional measurement and material characterization. Among the various techniques developed, digital signal analysis, image enhancement, distortion correction and intelligent data fusion are finding increasing application as NDE to assess structural integrity and to characterize materials.

9.5 Automotive Industries

Automotive industries were using more than 80% steel for fabricating automotive parts, and conventional welding methods for producing body structures. However, the situation has undergone drastic changes due to the following reasons:

- The industry has become highly competitive; hence, cost effectiveness has become a major production strategy
- There is demand for increased safety and conformance to strict environment regulations
- There is a desire to fulfill the needs of car owners for more luxury features
- There is demand for light-weight designs to save as much petrol and diesel as possible

These demands have necessitated the use of lighter materials like aluminum, magnesium, adhesives and composites, coupled with an innovative design approach and new joining techniques.

The introduction of lighter material components like aluminum- and magnesium-alloy castings, new welding technique and innovative design features coupled with the introduction of adhesive joints necessitates the introduction of commensurate NDE methodologies during manufacture and maintenance. The examination of welds and adhesive joints of metal plates and a combination of steel, polymer materials and glass has led to the application of high-frequency ultrasonics (A and C-scans) to assess the soundness of adhesive joints.

The inspection of aluminum and magnesium castings and fiber-reinforced composites is carried out by film radiography and computer tomography.

Tomography allows the detection and location of defects like porosity, shrinkage cavity and the determination of internal wall thickness and core mismatch. Low KV radiography is used to examine fiber-reinforced composites.

Apart from radiography and ultrasonics, other conventional methods are used for evaluating surface and sub-surface defects.

The objective of NDE is to control and monitor the quality, detection and evaluation of defects and wear analysis so that necessary action is initiated before premature failure of the component in service.

9.6 Offshore Gas and Petroleum Projects

NDE methods are extensively used in two major areas in offshore gas and petroleum projects, namely the fabrication of drilling platforms and the inspection of flexible pipes.

The main components of a drilling platform are legs and piles, which are tubular sections, welded together. The lower sections are larger in diameter and thicker than the upper sections. The structure has longitudinal and circumferential welds, which are examined by gamma radiography. Co-60 is used as the source of penetrating radiation.

Ultrasonic methods are also used to assess various weld joints. However, operators who perform the ultrasonic test must be approved as per the API guidelines for their qualification.

Initially, efforts are made to correlate radiographic and ultrasonic indications to establish confidence levels. Ultrasonic test methods include the pulse-echo as well as time of flight techniques. *A*-, *B*- and *C*-Scan methods of data presentations are used to indicate the condition of the entire volume of the welded area. The magnetic particle test and visual examinations are carried out to check for surface and sub-surface defects.

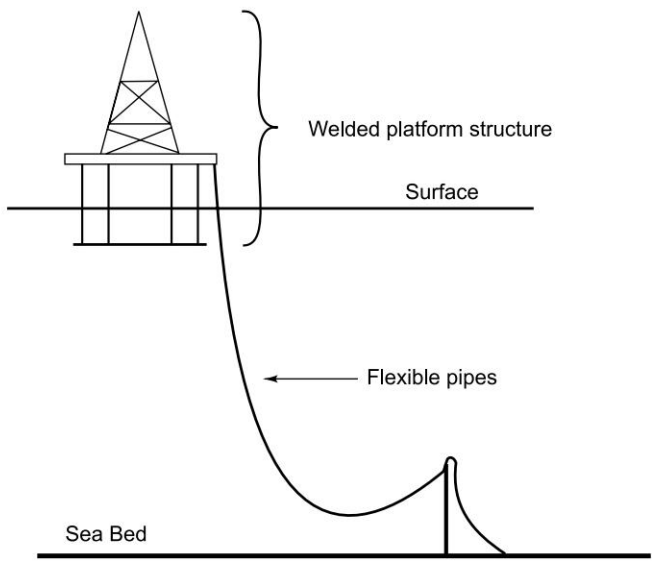


Fig. 9.4 *An Offshore Installation*

Flexible pipes are used for production, gas lift or water injection. These pipes are composite, multi-layered structures and are critical components of offshore exploration activity.

These pipes link the offshore platform and the wellhead on the seabed and are subjected to corrosion, erosion and fatigue. NDE inspection on these pipes includes visual examination using remote-operated vehicles or by divers, eddy current methods and X-ray radiography. Magnetic flux leakage methods are also being tried.

Considerable amount of development work is going into this area to develop adequate and cost-effective NDE techniques to monitor the components during service and repair.

In so far as the NDE of deep-sea installations is concerned, robot-based systems are used for inspection and maintenance. The usual problems that one encounters are those of cracks and corrosion in under-water components.

Advanced artificial intelligence techniques have also been developed to classify corrosion and cracks.

9.7 Coal Mining Industry

Non-destructive Test and Evaluation Methods are widely used in Coal Mining Industry to ensure freedom of mining equipment from harmful manufacturing defects, control of service and environment related defects during life cycle management and providing warning systems for prevention and control of accidents and dust control.

Mining Industries use hoisting system for moving personnel and material in vertical and inclined shafts through cage. Rope haulage system is used for transporting men, materials and waste. The systems use items like suspension gears pulley shaft and steel wire ropes. Transportation system either by hoisting or haulage are required to be reliable and safe during service.

The components of the systems show manufacturing defects like: cavities, porosity, shrinkages in castings and defects like-cavities, lack of fusion/penetration, lapping, lamination and surface and subsurface defects in welded items. During service, the defects that are generated are wear, fatigue cracks, corrosion and erosion.

Effect of various defects depend on their location, service and environment constraints and stress field. To ensure serviceability of components and assemblies, it is important to document acceptable defects depending on their morphology; in terms of size, number, proximity of defects and volume dispersion.

In so far as application of NDE is concerned following methods are regularly used:

- Visual Inspection to detect gross surface defects
- Magnetic particle test to detect surface and subsurface defects in ferromagnetic components
- Liquid penetrant test to detect surface defects in all components except highly porous components
- Eddy current test methods to detect surface and subsurface defects in conducting materials specially steel wire ropes for detection of broken wire and corrosion
- Radiography and ultrasonic methods find application to test and evaluate castings and weldments

Life cycle maintenance of components and assemblies requires periodic examination depending on accessibility, field condition and availability of equipment/test facility. Often times more than one complementary test may be required. Feedback from such tests may be used for risk assessment in allowing some defects for economic reasons or for realistic assessment of remaining life of components/assemblies.

Another area of importance and concern where NDE potential can be utilized is safety in coal mines. With increased focus on safety in underground coal mines, it is necessary to monitor parameters that affect safety and health of personnel. Parameters requiring regular monitoring are; gas concentration, underground water level, oxygen content, dust level, roof pressure, possibility of toxic gas emission and cave-ins.

Real time video monitoring can help removing miners to safe areas and protect them from dangers of ‘roof falling’. ‘Room and pillar’ mines require long distance connectivity for voice, location video processing to locate and help miners in distress.

A great danger in any mine disaster is low oxygen level and high carbon-dioxide level. Even low levels of carbon monoxide, methane gas, a mixture of nitrogen and carbon-dioxide is equally dangerous as they cause suffocation and death. Efforts need to be made to install electronic gas monitors and other warning systems for detection of toxic gases and provide necessary protection and supply of oxygen.

Occupational lung diseases like silicosis reduce life span of miners. To reduce this, analysis of the nature, size and volume per cubic meter of dust is essential. Routine dust analysis and innovative dust control mechanisms need to be installed.

NDE can play a significant role in this area through application of available methods and through dedicated R&D efforts.

10 Probability of Defect Detection and NDE

During the NDE of materials and components, one has to deal with a variety of data generated during testing and calibration. To extract the information contained in the data, statistical methods are needed to organize, analyze and interpret it. The data may be related to the manufacturing process, material property, structural integrity, size and distribution of defects/anomalies or the adequacy of NDE tools. The steps required to analyze and extract information include:

- Assessment of data distribution
- Study of the scatter and determination of the relationship between variables
- Assessment of the significance of the data and the level of confidence in the system

So far as NDE methods are concerned, it is important to appreciate that each NDE method is highly dependent on:

- Instruments and accessories used
- Conditions of inspection (e.g. indoor or outdoor testing, accessibility, skill of the operator and availability of reliable data for correct interpretation)
- Type of material/component under test

This makes the detection of defects and the repeated reproducibility of results highly probabilistic in nature. The probability of detection (POD) of defects is shown schematically in Fig. 10.1.

The probability of detecting a defect diminishes as its size decreases. This means that there is a minimum threshold size (a_0) that a defect must be to be detected using a particular technique in a given structure and inspection condition. The defect could be due to such factors as design, material, manufacturing processes, assembly, poor maintenance or error of individuals.

Non-detection of such defects is a potential risk, amongst others, for the failure of a structure or system. Therefore, for risk assessment, it is necessary to stipulate the biggest size of defect that may escape detection and be a possible cause of failure.

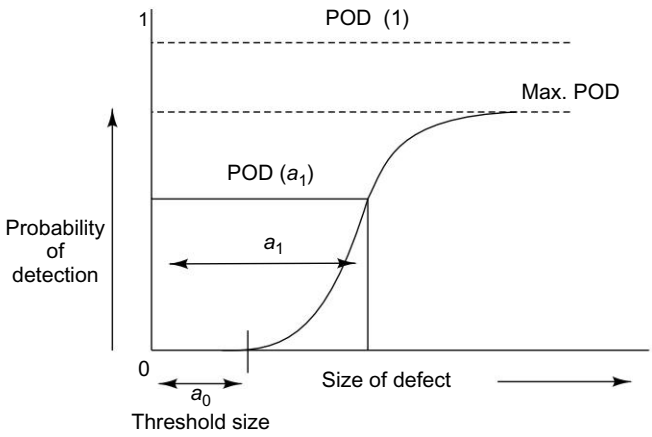


Fig. 10.1 *Probability of Detection (POD) of Defects*

The normal practice is to specify the threshold size of the defect (e.g. cracks in metallic structures and delamination in composites) at a high statistical confidence level and a high probability of detection, expressed as 95/90. This means that there is 95% confidence that 90% of all defects of this size or more will be detected under the specified test conditions and test environment.

Even with this approach there is a significant chance that defects larger than the specified threshold size will go undetected by a given NDE process.

We know that the POD is intimately connected with the probability of failure (POF). The POD depends on the material, component configuration and NDE methodology. The POF, on the other hand, depends on the distribution and nature of flaws, the character of the material and the load history. Often, designers stipulate the rejection of defects of a certain size (say, X). The NDE technologist attempts to establish a test methodology using round-robin procedures that would ensure 90% POD for the stipulated size X at 95% confidence level.

11

Modern Trends in NDE

NDE is an indispensable part of modern technology. It has emerged as a critical component of the engineering environment where cooperation and collaboration is a necessity. It is used during manufacture, design, inspection, repair and life-cycle management of engineering products and systems and is indispensable in the analysis of systems for safety, reliability and mission assurance. Conventional methods of NDE that have found application in various engineering activities are: Radiography, Ultrasonics, Magnetic particle test, Liquid penetrant test, Eddy current test. Other methods that are finding selected application, include Thermography, Acoustic emission, Microwave and Interferometric techniques. During last few decades, efforts were made to make instruments lighter, portable and sensitive to detection of finer defects. Efforts to utilize robot based computerized NDE systems, where large repetitive tests are required, is gaining acceptance. However, all these efforts are focused on detection of defects, training of personnel, preparation of techniques and documents and usage of environment friendly materials. Characterization of components and assemblies, in terms of design related properties (e.g. strength, stiffness, dimensions, corrosion, erosion, etc.) and structural significance of defects needs to be addressed seriously. This requires generating and validating related data and correlating these with NDE parameters. Often times more than one NDE test is required to provide confirming or providing additional information. It is possible to make use of such information if a compatibility of test results is established. To achieve this it is necessary to bit map graphic images of the defect in various orientations. Satellite mapping of images is a developed technology. This could be integrated in to the fold of NDE to achieve this objective.

In the decade of 80s and later there has been a galloping trend in the development and application of sophisticated materials and fabrication technologies coupled with innovative design methodologies and cost effective approach to life cycle management of components/assemblies/systems. This trend is going to continue. The demand in coming years would be to augment and develop NDE capabilities commensurate with specific requirements particularly in high-tech areas. There has to be a qualitative shift in approach from defect detection to characterization and evaluation of complex materials, data generation and analysis, keeping in view design stipulations. On line health monitoring of high duty components/

assemblies/systems would require focused attention. An understanding of physics, material science, manufacturing technologies and design demands will require generating a cogent mass of reference literature to be integrated in to the technology of NDE. Development of NDE tools (hardware and software) and test procedures to produce results that are quantifiable, repeatable and reliable, will need focused attention. Sufficient data needs to be generated to understand the mechanism by which an NDE tool interacts with test material in a given condition to bring out specific test data.

This will help proper interpretation of generated information. Further, greater interaction and cooperation with practitioners of R&D in other fields of science and technology will provide a better opportunity and ability to chart less understood areas of NDE. The task is formidable but there are no short cuts. This entails financial investment and dedicated study and research at academic centers and production organizations.

Application of NDE in high-tech areas call for the development of innovative concepts in assuring safety, reliability and maintainability during operational phase of systems. These demands necessitate integration of recent developments and discoveries in the fields of computers, satellite remote sensing technology, fast analysis and communication of data for dissemination of accurate information and effective implementation of monitoring facilities.

Other areas where NDE technologies would be required to play significant role are detection and prediction of environmental conditions that cause damage and destruction to life and property, sabotage, unethical and dishonest activities like-drug trafficking, hijacking of aeroplanes, criminal neglect of safety norms in factories, emission of toxic gases, nuclear radiation leak and prevention of accidents.

The technology of NDE can be an effective instrument in improving productivity and ensuring better quality of human life.

APPENDIX

TABLE OF CONSTANTS

Physical Constants

Usual Energy Range of Particulate Radiation

Alpha particles	4 – 8 MeV
Beta particles	0 – 4 MeV
Thermal neutrons	0 – 0.5 eV
Intermediate neutrons	0.5 – 10 KeV
Fast neutrons	10 KeV – 10 MeV
Very fast neutrons	More than 10 MeV

Electron = Mass: 9.11×10^{-28} gms; Charge: -1.6×10^{-19} coulombs or 4.8023×10^{-10} esu

Proton = Mass: 1.68×10^{-24} gm; Charge: 1.6×10^{-19} coulombs

Neutron = Mass: 1.67×10^{-24} gms; Charge: zero

'N' = Avogadro's number = 6.0226×10^{23} gm/mole

'h' = Planck's constant = 6.62569×10^{-27} erg$^{-\text{sec}}$

$h/e_{(1.37942 \pm 0.00002)} \times 10^{-17}$ erg$^{-\text{ sec/esu}}$

c = Velocity of light = 299,792.5 km/sec

M_1 = Mass of atom of unit atomic weight = 1.66045×10^{-24} gm

Volt = 1 volt = 1/300 esu = 10^8 emu

eV = one electron volt = 1.60×10^{-12} ergs.

1 Curie = 3.7×10^{10} Becquerel

1 Becquerel = one disintegration per second

X-Ray Absorption Coefficient

Wavelength (Å)	*Mass Absorption Coefficient in gms/sq.cm*				
	Carbon	*Aluminum*	*Iron*	*Copper*	*Lead*
0.02	0.0582	0.0559	0.0549	0.0542	0.0672
0.075	0.140	0.147	0.220	0.250	2.33
0.081	0.143	0.145	0.235	0.270	2.53
0.102	0.150	0.169	0.280	0.335	3.90
0.140	0.152	0.195	0.500	0.650	–
0.151	0.153	–	0.595	0.780	2.45
0.173	0.155	0.235	0.780	1.09	3.25
0.209	0.166	0.295	1.26	1.71	5.35
0.240	0.170	0.356	1.75	2.50	7.40
0.320	0.200	0.630	3.95	5.25	16.2

Frequency, Wavelength and Energy of Electromagnetic Radiations

Type of Radiation	*Frequency (F) (Hz)*	*Wavelength (Meters)*	*Photon Energy (eV)*
Radio waves	3×10^{8}	1	10^{-6}
Microwaves	3×10^{9}	10^{-1}	10^{-5}
	3×10^{10}	10^{-2}	10^{-4}
	3×10^{11}	10^{-3}	10^{-3}
Infrared	3×10^{12}	10^{-4}	10^{-2}
Visible light	3×10^{14}	10^{-6}	1
Ultraviolet light	3×10^{15}	10^{-7}	10
	3×10^{16}	10^{-8}	10^{2}
X- and Gamma-rays	3×10^{17}	10^{-9}	10^{3}
	3×10^{18}	10^{-10}	10^{4}
	3×10^{19}	10^{-11}	10^{5}
	3×10^{20}	10^{-12}	10^{6}
	3×10^{21}	10^{-13}	10^{7}
Cosmic rays	3×10^{22}	10^{-14}	10^{8}

Near Zone/Angle of Beam Divergence

Transducer	*Diameter*	*Water*		*Steel*		*Aluminum*	
F (MHz)	*D (mm)*	*N (mm)*	γ^o	*N (mm)*	γ^o	*N (mm)*	γ^o
2	24	195	1.5	49	6.2	46	6.6
2	5	8	7.4	2	31.0	2	33.2
4	24	389	0.8	97	3.1	91	3.3
4	5	17	3.7	4	14.9	4	15.9
12	10	203	0.6	51	2.5	48	2.6
12	5	51	1.2	13	4.9	12	5.2

Decibel-Power Ratio Relationship

dB	0	1	2	3	6	10	20	40	60	80
Ratio	1:1	1:1.12	1:1.26	1:1.41	1:2	1:3.16	1:10	1:100	1:1000	1:10000

$$V = 20 \log \frac{a_1}{a_2} \text{ (dB)}$$

where a_1 and a_2 – Difference in voltage or power

$$\frac{a_1}{a_2} = \text{voltage/power ratio}$$

Conversion Table

Material	*Resistivity (ρ) (Micro ohm centimeter)*	*Conductivity (σ) (% IACS)*
Graphite	689.6	0.25–0.35
Manganese	191.5	0.90
Nimonic 105	131.0	1.316
Nimonic 80 A	124.0	1.390
Nimonic 90	115.0	1.500

(*Contd*)

Resistivity and Conductivity of Materials

Material	*Resistivity (ρ) (Micro ohm centimeter)*	*Conductivity (σ) (% IACS)*
Nimonic 75	109.0	1.582
Titanium	71.8	2.40
Stainless steel	70.0	2.46
Uranium	66.3	2.60
Zircalloy	66.3	2.60
Bronze (S1)	18.1	6.5–12.0
Lead	20.2	8.5
Chromium	19.1	9.0
Aluminum (Cast)	17–38	10–45
Bronze (P)	10.7	11–18
Bronze (Mg)	11.4	12–18
Tin	11.4	15
Bronze (Al)	12.3	12–17
Nickel	10.9	15.8
Platinum	10.4	17.0
Iron	9.8	17.6
Brass (yellow)	7.8	18–25
Brass (30% Zn)	6.1	28
Zinc	5.9	29
Cobalt	5.6	30.7
Tungsten	5.3	32.0
Molybdenum	5.2	33.0
Brass (15% Zn)	4.6	37.0
Magnesium	4.4	39.0
Brass (5% Zn)	3.1	55
Aluminum (wrought)	2.6	65
Gold	2.2	75
Copper	1.7241	100
Silver	1.642	105

Conversion Factors

From Resistivity (ρ)	*To Conductivity (σ) (% IACS)*	*From Conductivity (σ) (% IACS)*	*To Resistivity (ρ)*
Micro ohm centimeter	$\frac{1}{\rho} \times 172.41$	Ohm-inches	$\frac{1}{\rho} \times 67.87$
Ohm-meters	$\frac{1}{\rho} \times 1.7241 \times 10^{-6}$	Ohm (meters mm^2)	$\frac{1}{\rho} \times 1.7241$
Ohm-Centimeter	$\frac{1}{\rho} \times 1.7241 \times 10^{-4}$	Relative resistivity	$\frac{1}{\rho} \times 100$

Density Modulus, Ultrasonic Velocity and Specific Acoustic Impedance of Materials

Materials	*Density* (g/cm^3)	*E* (kg/mm^2)	*Velocity (m/sec)*		*Z*(g/cm^2 sec. $\times 10^5$)
			V_L	V_T	
Air	0.0012		330		0.0004
Aluminum (alloy)	2.7	7000	6320	3040	17.0
Barium titanate	5.7	–	6050	–	34.4
Brass	8.2	10000	4420	2110	31.0
Copper	8.9	12500	4770	2250	41.6
Glass	2.5	7200	5660	3420	14.1
Ice	0.9	–	3980	1990	3.5
Iron-cast	7.6	10000	3400–5600	2100–3200	25.8 – 42.5
Iron-wrought	7.8	21700	5920	3230	46.1
Lead	11.4	1660	2160	710	24.6
Magnesium	1.8	4200	5960	2910	10.7
Nickel	8.8	20540	5630	2960	49.5
Oil	0.8	–	1410	–	1.12
Quartz	2.6	7570	5680	3490	15.0
Rubber	1.0	–	1500–2300	–	1.5 – 2.3
Steel	7.6	21000	5950	3250	45.2
Tungsten	19.1	36200	5460	2620	104.2
Tin	7.3	5540	3320	1670	24.2
Zinc	7.1	10500	4100	2400	29.1
Water	1.0	–	1480	–	1.4
Perspex	1.2	500	2680	1320	3.4

REFERENCES

1. Non-Destructive Hand Book—American Society for Non-Destructive Testing.
2. Metals Hand Book—Volume 17—ASM International Hand Book Committee.
3. Treatise on Non-Destructive Testing and Evaluation (3 Volumes) J Prasad, H S Ganesha, T Rangachari & B N S Murthy.
4. Principle of Penetrant—Carl, E Betz.
5. Principle of Particle Inspection—Carl, E Betz.
6. Non-Destructive Testing—Warren, J McGonnagle.
7. Non-Destructive Hand Book—R Hamsaw.
8. Risk Based Assessment of Industrial Components and Plants—M Croning & D D Dioclov.
9. The Significance of Defects & Damages in Composite Structures—R T Potter—AGARD Conference Proceedings 335.
10. Strategically Analysis for Decision Making—Moris Hamburg.
11. Juran's Quality Hand Book—McGraw-Hill.
12. Ultrasonic Testing of Materials J Craut Cramer & H Craut Cramer.
13. Ultrasonic Low & High Energy Application—Dale Ensmingal, Marcel Dekar.
14. Ultrasonic Theory & Application—G L Gooberman.
15. Research Techniques in NDT—Edited by R S Sharp.
16. Non-Destructive Characterization of Composite Media—Ronald A Klim.
17. Role of Modeling and Simulation in Development of Advanced Non-Destructive Evaluation System—E R Generazio & C F Harris—Aeronautical Journal, July 1999.
18. Recommendation of International Commission on Radiological Protection.

INDEX

U

W

X

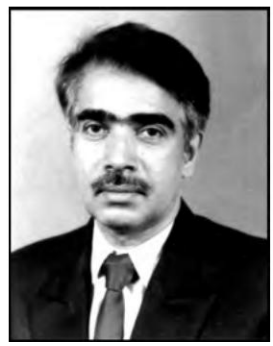
Authors' Profiles

Prof J Prasad is an authority in the field of Non-Destructive Testing and Evaluation. He has over the past three and a half decades made significant life time contributions in the development of NDE technology.

Prof Prasad obtained his Masters' degrees from the University of Patna and University of Sheffield (UK). He has been actively associated with training, development of techniques and test facilities, documentation, R & D and archiving aspects of NDE technology, as the head of Centre of Excellence in NDT at Hindustan Aeronautics Ltd and as the head of NDT projects at Aeronautical Development Agency (Light Combat Aircraft Project). He has trained at NDT Centre over thousand NDT engineers/technicians. After retirement from Aeronautical Development Agency, he has served as Specialist Consultant to Government and private organizations and academic institutions in areas related to NDE of metallic and composite materials.

He is associated with a number of professional associations and is the Founder Chairman of Bangalore Chapter of NDT Society of India. He is a fellow of Ultrasonic Society of India, member of NDT Society of India, Acoustic Emission Group of India and a professional member of ISAMPY, etc. Prof Prasad has published and presented more than 60 research papers at National and International Seminars, and authored seven books and manuals, specifically related to various disciplines of NDE, including three volumes on 'Treatise on NDT'. He has also chaired a technical session of the 11th World Conference on NDT at Las Vegas, USA. He has coordinated and guided development of a multi-axis, robot based C-Scan System for test and evaluation of large fiber-reinforced composite components. He has been associated with the Department of Science and Technology in NDT Laboratories' accreditation programme and Indian Bureau of Standards (NDT Sub-Committee), and has been visiting Professor/Consultant in the field of NDE.

He has widely traveled various countries in Asia, Europe and USA for discussion, training and technical presentations in various disciplines of NDE.



Dr C G Krishnadas Nair is a graduate in metallurgical engineering from IIT Chennai and PhD from the University of Sask, Canada. After a brief academic career he joined Hindustan Aeronautics Ltd, and served in many responsible positions and retired as Chairman and Managing Director of the company. After retirement from HAL, he served as Vice Chancellor of Mahaveer Academy of Technology & Science (MATS) University. Currently, he is an AICTE-INAE Distinguished visiting professor and IIT Chennai and Principal Advisor to Jain Group of Educational Institutions. He is associated with a number of Engineering

Professional Associations and the Founder President of the Society of Indian Aerospace Technologies & Industries (1995–1997). He is a fellow of the Indian National Academy of Engineers, Institution of Engineers India, Aeronautical Society of India, Indian Institute of Metals, NDT Society of India, and Indian Society for Advancement of Materials and Process Engineering. He is a board member of many private and public sector industries and was member of many scientific advisory committees.

Dr Nair set up a Centre of Excellence in NDT at HAL along with his then colleague Mr J Prasad. The Centre has trained over a thousand NDT Engineers/technicians and developed a large number of NDT techniques for aerospace structures and components. Dr Nair was Chairman, Technical Committee for the International World Conference on NDT held in India in December 1996. He has published 160 scientific and technical papers in the field of materials testing including NDT and has authored 20 books in the field of aerospace materials, quality assurance, engineering and management.

Dr Nair is a recipient of several awards which include Padma Shri, National Aeronautical Prize, Birla Gold Medal, National Metallurgist Award, Vasvik Research Award, Shri Om Prakash Bhasin Award for Space & Aerospace, Indira Gandhi Priyadarshini Puraskaram, SCOPE Award and Gold Cup for excellence in Public Sector Management, and Engineers' Life Time Contribution award from Indian National Academy of Engineers.